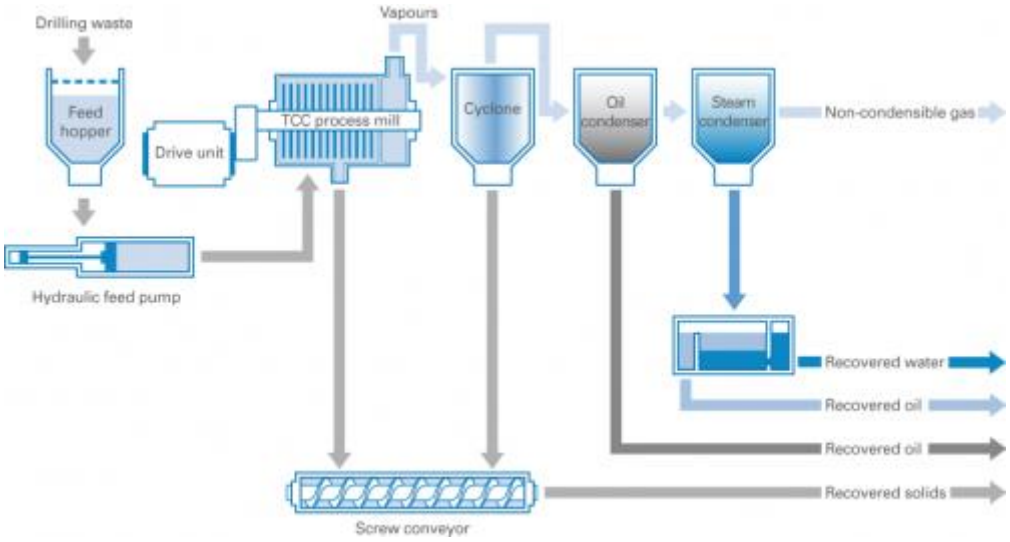
Characterising Thermal Treated OBM Drill Cuttings

Sampling, characterisation, environmental analysis and risk assessment of offshore discharges



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A separate appendix report has been prepared with analysis results and test reports. The Norwegian version of the report was completed on January 9th 2014 (version 4)

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Content Table

Abbreviations

Abbreviation	Terminology
CP	Cyclo-pentane
dm	Dry matter (solids in samples)
dvm	Dry volatile matter
DREAM	Dose Related Environmental Assessment Model
EB	Emulsion breaker
EQS	Environmental quality standard
ERMS	Environmental risk management system
EU/EC	European Union/European Commission
HSE	Health, safety and environment
LCA	Life-Cycle Analysis
$L(E)C_{50}$	50% lethal (effect) concentration
LOQ	Limit of quantification
LS	Liquid solids fraction
LSC	Level of significant contamination
MARA	Microbial Array for Risk Assessment
MOD	Environmental MOnitoring Database
MWM	Mowing window modelling
NCS	Norwegian continental shelf
NPD	Naphthalene, penanthrene and dibenzothiophene
OBM	Oil-based mud
OSPAR	Oslo-Paris convention for the protection of the marine environment of the north-east Atlantic
PAH	Polycyclic aromatic hydrocarbons
PEC	Predicted environmental concentration
PLC	Programmable logic controller
PNEC	Predicted no effect concentration
PSD	Particle size distribution
QS	Quality standard
ROP	Rate of penetration
SEM	Scanning electronic microscopy
SBM	Synthetic-based mud
SDR	Solids recovery
SS	Suspended solids
SSD	Species sensitivity distribution
TCC	Thermomechanical Cuttings Cleaner
TGD	Technical Guidance Document
THC	Total hydrocarbon concentration
TPS	Thermal phase separator
TSS	Total suspended solids (in water samples)
TU	Toxicity unit
UKCS	UK continental shelf
VDM, VSS	Volatile dry matter (solids samples); volatile suspended solids (in water samples)
VOC	Volatile organic carbon
WAF	Water accommodated fraction
WBM	Water-based mud
WSD	Water-soluble derivative

Summary

The Norwegian Oil and Gas Association took the initiative to implement this project to enlight on environmental issues related to offshore thermal treatment of drill cuttings contaminated with oil-based mud (OBM cuttings). The purpose of the project has been to secure data on the physical-chemical and environmental-toxicological properties of such cuttings after treatment. Collated data should be used to assess the environmental consequences of discharging thermal treated OBM cuttings offshore.

The project has had a steering committee drawn from participating oil companies. Einar Lystad at Norwegian Oil and Gas Association chaired the work group, which comprised of:

- Ståle Teigen, Nina Aas, Torgrim Svensen and Tone Karin Frost, Statoil
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In addition to the oil companies, TWMA, Halliburton, Schlumberger/MI-Swaco and Thermtech AS have assisted in acquiring data from the treatment of cuttings. The operator companies have also contributed other expertise where that has been necessary for successful implementation of the project. Lundin has contributed by obtaining three sample series for the study.

The project was initiated because Norway prohibits the discharge of OBM cuttings to the sea, and since no OBM cuttings treatment technologies are currently approved on the NCS for treatment of OBM cuttings before discharge, normal practice in Norway is to transport the cuttings to land for treatment and deposition. Discharging TCC-treated OBM cuttings has been approved on the UKCS since 2003. Several different treatment technologies are under development nationally and internationally. Norway's offshore activities regulations specify that discharges to the sea are not permitted on the NCS if the oil content adhering to solids is > 10 g/kg dm (>1 %) . Based on information from the supplier, OBM cuttings treated with the TCC technology should satisfy such a requirement.

The heart of the TCC technology is the Hammermill process. No external heat is added, but frictional heat creates a temperature of 250-300°C. Base oil is recovered and reused, and the water is treated in a condensation process. The base oil is a low-aromatic hydrocarbon (C_{16}-C_{22}) with low toxicity, which degrades easily, but which has a high log P_{ow} value. According to the Norwegian Environmental Agency, it is classified as yellow.

Experience with operation of the TCC technology on the UKCS has been assessed. A report is available with documentation of the results of the treatment process offshore. This showed that the oil content adhering to the cuttings during such an operation has an average of 0.4 g/kg dm, and that the water maintains an average oil-in-water concentration of about 12 mg/l. These results are better than those previously reported from sampling of the TCC facility on Oseberg South, which could suggest that opportunities exist to achieve better results when the treatment is conducted with fresh cuttings samples offshore than when the samples have been stored and transported ahead of water treatment.

The Norwegian oil industry needs alternative environmentally-acceptable solutions to transport ashore for handling OBM cuttings, and accordingly wants to understand the environmental consequences of discharging TCC-treated OBM cuttings to the sea on the NCS. The plan was for this project to collect samples from offshore installations with installed thermal treatment facilities for OBM cuttings. However, it proved difficult to find suitable operations. It was accordingly decided to collect samples from land-based TCC facilities with

reception of OBM cuttings. Samples were taken in and out of the facilities at Mongstad South and Cuxhaven in Germany. A total of four sample sets (including three from the NCS with detailed information on the geology) were collected and investigated. Particle form and particle size distribution (PSD), physical/chemical parameters and priority pollutants were determined in samples of untreated and treated OBM cuttings. Sedimentation and leaching tests have been conducted with treated OBM cuttings and ecotoxicological analyses (Microtox, Mara, *Skeletonema* and *Acartia*) carried out with leachate. *Calanus finmarchicus* has been tested in water with and without particles. The toxicity of treated cuttings has also been tested with asediment reworker *Corophium volutator*.

Dispersion modelling of discharged TCC-treated OBM cuttings from a representative well on Ivar Aasen (water depth 113 metres and discharge one metre below the sea surface) has been conducted by SINTEF for a summer and a winter situation. Aquateam COWI have assessed the results of the modelling with the eye of utilising them in environmental risk assessment of discharges from the TCC process during offshore treatment of OBM cuttings. The dispersion model shows that the maximum concentration of treated OBM cuttings in the water column can reach 1-5 mg/l at the maximum, and that the maximum thickness of the cuttings on the seabed occurred 250-300 metres from the discharging rig. In an area equivalent to 50 x 50 metres, this thickness can reach 1.8 mm. That represents a considerably higher figure than with corresponding modelling on the UKCS. The quantities discharged are also significantly larger. OBM cuttings are assumed to be used in the three lowest sections (17½, 12¼ and 8½ inches) in the Ivar Aasen well.

Norwegian specialists have carried out a number of substantial research and monitoring projects to understand the environmental impact of discharging WBM cuttings. Such discharges have been shown to have short-term effects on sediment-dwelling organisms up to 250 metres from the discharge site. Studies of corals show that these can remove six mm of cuttings sludge but not 19 mm (test concentrations). SINTEF's dispersion modelling showed that sludge on the seabed would have a maximum thickness of 1.8 mm. Results from the PROOF research project also showed that suspension of cuttings with barite has led to reduced growth and feed uptake for juvenile cod, and effects have been demonstrated down to 0.5 mg SS/l for cod and mussels:

- Additional loading of 0.15 mg SS/1 has a stress effect on phytoplankton
- A cumulative effect in the water column is unlikely.

Effect concentrations of relevant priority pollutants have been assessed and PNEC values have been proposed for all relevant priority pollutants. The environmental quality of treated OBM cuttings is compared with sediment quality (based on quality standards). Effects on the water column (with and without particles) and on sediment have been assessed on the basis of measured toxicity data, calculated dilution from SINTEF's dispersion modelling and available effect data from the literature. Available effect data (PNEC) for sediment from offshore studies vary in relation to recently calculated environmental quality standards. These assessments have been made on the basis of both data sets. That yields somewhat varying results, but the conclusions are the same once dilution is taken into account.

Based on sampling, analyses and environmental risk assessment of offshore discharges of thermal treated OBM cuttings to the sea, compared with the results of monitoring and studies conducted on the effect of discharging WBM cuttings, the following conclusions have been drawn:

- Environmental risk associated with the discharge of thermal treated OBM cuttings will correspond to that seen with discharges of WBM cuttings.
- The levels of oil, PAH and metals in treated OBM cuttings are expected to lie at the same level as for WBM cuttings.

- The only environment-related footprint which might be demonstrated through monitoring relates to particles and sludge deposition in areas with the highest sedimentation of cuttings. The chemical pollution is expected to have a negligible effect on both water-phase and bottom-dwelling organisms. No effects are expected in the water column.
- Because particle size for thermal treated OBM cuttings is somewhat smaller than for WBM cuttings, sludge deposition may be somewhat smaller.

However, this conclusion should be verified with the following investigations:

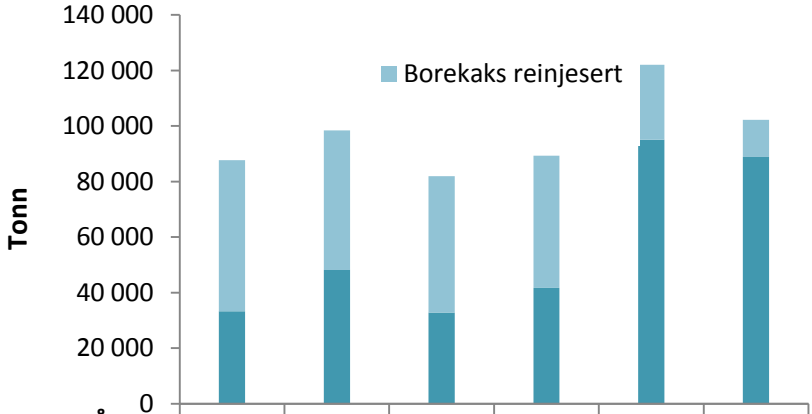
- Follow-up of installations on the NCS
  - mapping discharges of cuttings, oil and water
  - modelling dispersion of the discharges
  - conducting a risk assessment based on actual discharges.
- Background data from environmental monitoring in 2012 should be reviewed, and PNEC and EQS values established for the water column and sediments in various regions of the North Sea.
- Sources of heavy metals in sediment/cuttings should be investigated. Various barite types should be analysed for heavy metal content. Should large differences be found, checks should be made to see if this can explain the variations in background values found in different parts of the North Sea. The need to establish performance specifications for barite should be assessed.
- The reason for oxygen consumption by cuttings in ecotoxicity tests should be clarified, and tolerance levels for oxygen and pH in *Calanus finmarchicus* and *Corophium* clarified with a view to utilising this type of test to follow up studies of the effects of cuttings dispersion.

1. Background

1.1. Regulations and operating parameters

Environmental monitoring of discharges from the petroleum industry has been conducted since 1973. In the early phase of Norwegian oil and gas production, up to the early 1990s, this activity was directed primarily at monitoring sediments for effects from the discharge of drill cuttings. Results from this monitoring led to new discharge requirements for of cuttings with more than one per cent by weight of adhered oil being prohibited on the NCS in 1992. This prohibition was also extended to the whole OSPAR area in 1992 (Paris commission decision 92/2). After the ban on discharging oily cuttings and the increase in produced water discharges during the 1990s, the possible negative environmental effects in the water column have attracted greater attention. The HSE regulations currently require that both sediment and water column are monitored. Until 1996, the operators conducted individual surveys on an annual basis around their own installations. Regional surveys have since been conducted, with the operators collaborating over monitoring in each region. The programme covers chemical analyses of hydrocarbons, selected heavy metals and radioactive substances, and analyses of possible changes in the composition of the benthic community.

Treatment and final disposal of OBM cuttings are largely conducted today through transport to land and treatment, or through injection into the sub-surface on the field (offshore). Det Norske Veritas (DNV) produced a report in 2012 which assessed oily waste from offshore petroleum operations (Karlsen, 2012). The quantity of general oily waste was stable in 2006-089, but rose markedly in 2010-11. See Figure 1. This partly reflects problems with injection on a number of fields, where the injection wells had to be shut down during 2010. Another reason for the rise was that the practice of slurryfication of cuttings with slops and drilling mud continued even after the injection wells were shut in (Karlsen, 2012). On some fields, the total quantity of drilling waste for treatment on land increased. In addition, the quantity of cuttings and other oily waste rose because drilling increased in 2010. New injection wells were drilled in 2012 on certain fields, but this was not possible on all fields – particularly the new ones. The DNV report concluded that no capacity problems related to treatment would arise at a national level, but that local challenges could occur. This conclusion was based on forecasts and various available treatment scenarios, with one scenario including treatment solutions based on using TCC offshore and increased injection capacity compared with the position experienced in 2010.



År	2006	2007	2008	2009	2010	2011
Borekaks reinjesert	54 433	50 321	49 108	47 640	26 938	13 292
Borekaks sendt til land	33 308	48 131	32 795	41 714	95 088	88 911

Key: Tonn = Tonnes; Borekaks reinjesert = Cuttings re-injected; År = Year; Borekaks sendt til land = Cuttings shipped onshore

Figure 1. Developments in the quantity and disposal of oily drill cuttings from 2006 to 2011 (Karlsen, 2012).

1.2. The Norwegian Oil and Gas Association project

Members of the Norwegian Oil and Gas Association have taken the initiative to investigate the opportunities for qualifying thermal treatment by the TCC (thermo-mechanical cuttings cleaner) technology for offshore treatment of OBM drill cuttings. The limited opportunities for injecting cuttings (new fields and wells) make onshore treatment of OBM cuttings the only option for Norwegian operators. Increased drilling activity creates high challenges for the operators. It provides low operational flexibility, since the capacity for treating cuttings onshore is currently limited. Available treatment capacity and solutions cause delays to and enhance the cost of planned drilling activities for a numerous operators.

Qualified technology can be found today for treating OBM cuttings offshore, including on the UKCS. Offshore treatment of OBM cuttings has since 2003 been operational on the UKCS. Assessments of the results achieved have been promising, and a desire accordingly exists to investigate the opportunities to qualify this technology for use also on the Norwegian Continental Shelf (NCS).

The Norwegian Oil and Gas Association took the initiative to implement this project to enlight on environmental issues related to offshore thermal treatment of drill cuttings contaminated with oil-based mud (OBM cuttings). The purpose of the project has been to secure data on the physical-chemical and environmental-toxicological properties of such cuttings after treatment. Collated data should be used to assess the environmental consequences of discharging thermal treated OBM cuttings offshore.

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A great deal of data is available on the environmental properties of cuttings following treatment with the thermal technology. Aquateam COWI has accordingly reviewed existing test reports and documentation on chemical analyses, toxicity and particle sizes in order to collate existing information. Earlier life-cycle analyses and reports have also been collated and summarised by the project. In addition, new samples of OBM cuttings have been taken before and after treatment with TCC. These have been secured in order to obtain missing information and to verify findings from the literature.

The project began in January 2013. A kick-off meeting was held in February, followed by steering committee meetings in May, June and September. The project has been implemented by Aquateam COWI, with Statoil contributing specialist expertise and results from internal studies conducted by the company. Lundin has contributed by obtaining three sample sets of untreated and treated OBM cuttings. One sample set has been provided by M-I Swaco from Germany. These samples have been used in the investigations conducted in this project.

1.3. Environmental impact of discharging WBM drill cuttings

Monitoring data from existing fields show developments in the concentration and dispersion of various priority pollutants and oil in sediments derived from drilling activities over a number of years.

Regular monitoring is conducted with North Sea sediments affected by offshore oil operations. Monitoring by Akvaplan-Niva in 2006 (Renaud et al, 2006) updated results from 2000 in order to determine the area with a significant increase in the content of barium (Ba), oil (THC) and heavy metals. The 2006 monitoring concluded that 0.1 per cent of the area on the NCS is contaminated or affected by offshore activity. This report also identified important aspects related to monitoring strategy, and concluded that the current division into regions was appropriate and that sufficient knowledge was available to select representative reference stations for monitoring.

The monitoring programme has a number of reference stations in 11 regions along the coast, in the Barents Sea and around the coast of Svalbard. In 2006, seven of these regions embraced producing oil and gas fields. Attention related to monitoring discharges from offshore drilling activities is concentrated on barium, which is used to map historical and current discharges from drilling operations. Samples are also taken for heavy metals, THC and selected priority pollutants including PAH and NPD.

Locally, close to older installations, a reduction has occurred in the content of THC in the uppermost sediment layer which partly reflects changes in the discharge of OBM, SBM (synthetic based mud) and now WBM drill cuttings. After 3-6 years, natural fauna had re-established itself in a number of localities since the 2000 survey. Effects like this were not general for regions and stations, which is attributed to constant remobilising and churning of polluted sediment. That is caused by such factors as bioturbation, storms, and changed operating conditions with moving, mooring and laying of pipelines. Big annual changes were observed in fauna which could be caused just as well by modifications to operational activities and natural variation in the ecosystem as by alterations in discharges from the installations. Careful selection of monitoring localities is accordingly important, particularly where habitats are heterogeneous.

These experiences show that it can be difficult to observe significant effects related to a possible discharge of treated OBM cuttings through general monitoring before it has been underway for a number of years. So many different operating factors in the petroleum activity influence the effect on fauna in seabed sediments that this share of the discharge will not be picked up.

No OBM drill cuttings have been discharged to the seabed on Troll, and the THC content in sediments on this field are low. The water depth on Troll is relatively large, 350 metres. WBM has been used, and Figure 2 shows that that the largest quantity of WBM drill cuttings is found in sediments at station C-02. The barium content indicates where the largest quantity of WBM cuttings is found. The THC content of the WBM cuttings discharged lies in range of 0.1-0.3 per cent, or 1-3 g/kg dm.

Monitoring results from Troll B and C show that the THC content on the seabed declined from the time these observations began in 2004 until 2010. See Figure 3 (Nøland et al, 2011). All stations had THC concentrations below the LSC. PAH and NPD above the LSC were found at one station. No significant changes were registered in the faunal community since the 2007 investigation, and the benthic fauna in the area was assessed to be undisturbed. A general decline in THC concentrations for Troll A was also registered at all the stations in 2010 compared with the 2007 investigation. See Figure 4. The concentrations lie in the range from 9-13 mg/kg, and no increase in THC values was registered. Results from Troll indicate that THC released during earlier drilling operations has been broken down

over time. On the basis of these investigations, Statoil has concluded that sediment samples show high barium concentrations from discharges of WBM cuttings while THC is at the background level. The dispersion pattern for WBM cuttings means that THC is broken down continuously, and similar effects are expected from the discharge of thermal treated OBM drill cuttings (after TCC treatment).

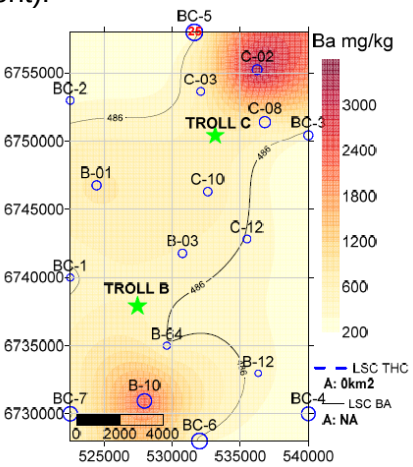


Figure 2. WBM cuttings have been discharged on Troll C. The colouring scale on the right side shows measured content of Ba (mg/kg) throughout the field. The Figure shows the various monitoring stations, including C-02, which has the highest deposition of WBM drill cuttings indictaed by Ba concentration (Nøland et al., 2011).

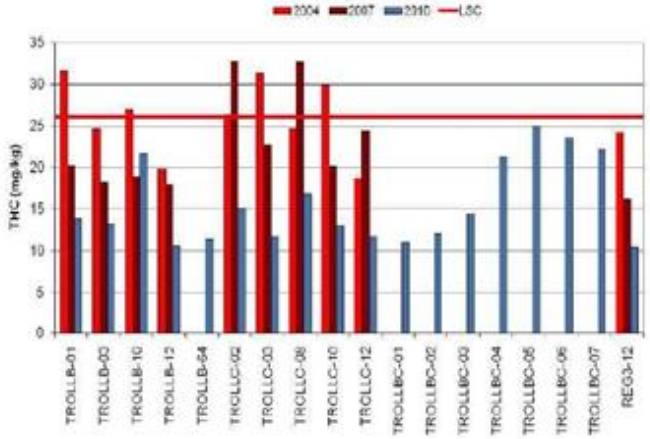


Figure 3. Development of THC (total hydro carbon concentration) from 2004 to 2010 on the monitoring stations on Troll B/C (Nøland et al., 2011).

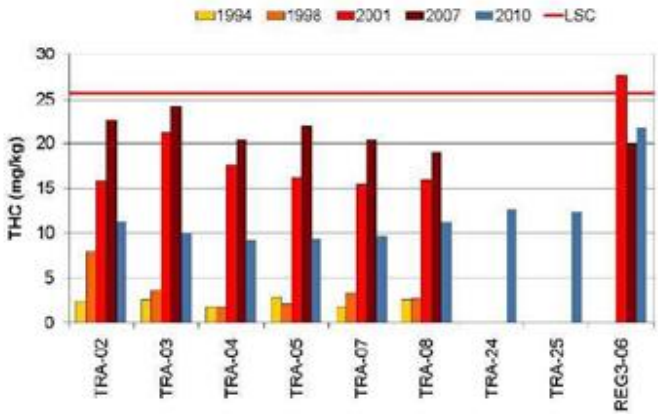


Figure 4. Development of THC from 1994 to 2010 on monitoring stations on Troll A. LSC is the level of significant contamination (Nøland et al., 2011).

1.4. Discharge of THC from TCC treated OBM drill cuttings – operational data

With a TCC facility installed offshore on the UKCS, TWMA has logged operating data and written a report for the complete drilling operation with OBM (Graham, 2010). OBM was used in three different sections – 17½ inches of 2 875 metres with 696 tonnes of cuttings, 12¼ inches of 933 metres with 511 tonnes, and 8½ inches of 295 metres with 18 tonnes. See figures 5-7. The results of the study showed the following.

- The average oil content in the cuttings before treatment was 31, 30.2 and 32 % for the 17½-, 12¼- and 8½-inch sections respectively.
- The average quantity of recovered base oil was 97.38 % from the 17½-inch section.
- The total quantity of treated cuttings discharged was 1 050 tonnes, including 98.9 kg of adhered oil.
- 160 m^3 of water was discharged, containing 1.1 kg of oil in total (oil in water).
- The concentration of oil on treated cuttings and in the water phase was stable throughout the treatment operation.
- The maximum concentration of residual oil was 0.08 % in the cuttings, corresponding to 0.8 g/kg dm. The average was 0.03 %, corresponding to 0.3 g/kg dm of cuttings. These operational values are in accordance with the technology supplier's specifications and are well within the requirements in section 68 of the activities regulations on the discharge of sand and solid particles, which are oil < 1 % or < 10 g/kg dm. In its data sheet (safety data sheet TWMA dry matter, 2012), the supplier specifies the following content:
    - THC 2.247 g/kg dm
    - Total content of aromatics: 178 mg/kg dm
    - PAH: 1.1 mg/kg dm

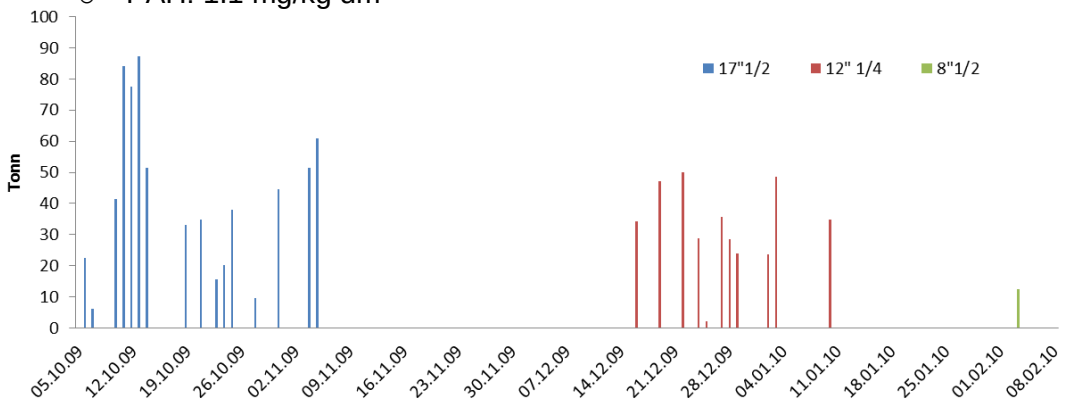


Figure 5. Quantities of TCC treated OBM cuttings discharged from drilling operation in 2009-10, broken down by three different well sections (Graham, 2010).

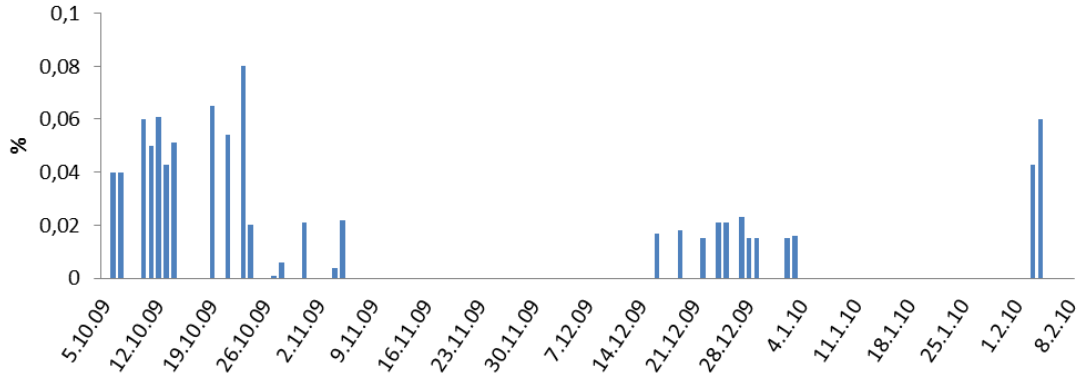


Figure 6. Concentration of oil (per cent) in treated cuttings discharged (Graham, 2010).

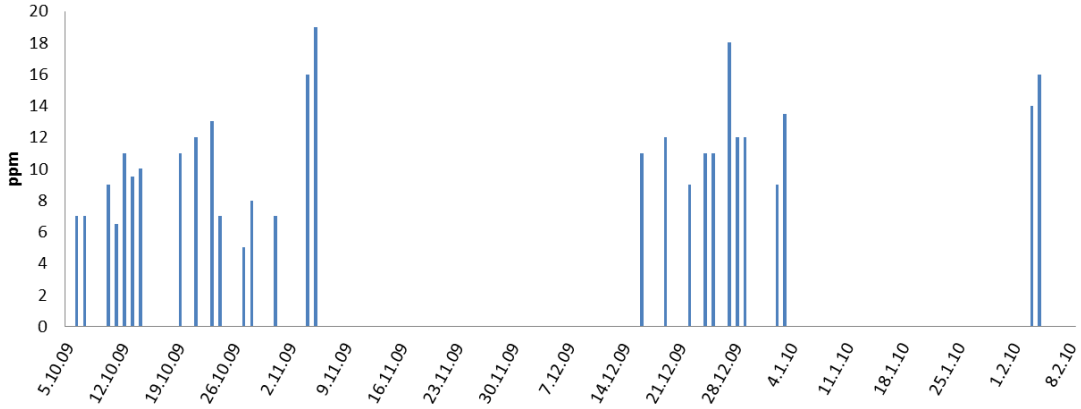


Figure 7. Concentration of oil-in water (mg/l) in treated cuttings discharged (Graham, 2010).

1.5. Dispersion of discharged TCC treated OBM cuttings

Cordah (2005) modelled the dispersion of discharged treated crushed cuttings after offshore treatment with the TCC technology. BMT's Proteus model was used, and the basis for the modelling was drilling the 12¼-inch section and a discharge volume of 177 m^3 of treated OBM cuttings. The discharge point was three metres beneath the sea surface, and the drilling operation lasted for 10 days. Modelling the dispersion of the cuttings showed that the thickness of the particle layer on the seabed was limited, with a maximum of 5.5 µm. The particle distribution was influenced more by local hydrodynamic conditions than by sedimentation speed, and the bulk of the cuttings dispersed over a large area.

2. Thermal technologies for treating OBM drill cuttings

2.1. Different technologies

Various types of thermal treatment technology are available for cuttings. OBM cuttings are crushed and heated to a temperature which is high enough for oil and water to vaporise and thereby disappear from the cuttings. The liquid is separated from the solids, with oil and water condensed later in the treatment process. This process is also called “thermal desorption”.

Several types of technologies use external heat sources to heat the OBM cuttings before oil and water are removed. Some examples of solutions on the market include TCC, solid recovery (SDR), thermal phase separator (TPS) and Porcupine (Bethlehem).

Most of the thermal technologies use an external heat source, and are based on passing the cuttings over large heated surfaces in a transport screw, on discs or in a rotating drier. These processes require relatively substantial space and are therefore utilised mainly in land-based installations. The recovered oil achieves seldom a quality (cracking) allowing for it to be re-used as base oil after separation. The long time spent in the separator and the high temperature effect on oil which it is subjected to when an external heat sources are used deteriorates the quality of the oil.

Of the four above-mentioned technologies, only TCC has so far been qualified for offshore use by the oil companies operating in the OSPAR region. This is also the technology utilised in this project. Heating is achieved through mechanical friction in the Hammermill. No external heat is supplied.

2.2. Thermo mechanical cuttings cleaner (TCC)

TCC® is based on the principle of thermal separation. Developed by Thermtech AS, it has been licensed to various operators – including TWMA, Halliburton, Slumberger/MI-Swaco and SAR. Norway currently has several land-based facilities which treat OBM cuttings using TCC technology, but most of these primarily treat a mixture of oily drilling waste, solids and slop. As defined by Norsas (2007), slop is an oil/water blend which contains no rock fragments from drilling.

The technology uses frictional heat generated by crushing rock in the mill as the sole energy source for the thermal separation process. The highest temperature in the mill is found within the actual particles as a result of the frictional heat. A common description for this type of thermo mechanical mill is a Hammermill or Rotormill. The process start-up includes adding sand and, once a sufficiently high temperature has been reached, the cuttings to be treated are added. The liquid phase vaporises/condenses and is separated into dedicated tanks for water and oil. Cuttings are fed continuously into the mill once the temperature reaches a desired level. The resulting dry matter (dm) – in other words, the crushed rock – is emptied from the mill on the basis of set values. The whole process is run automatically with the use of PLC systems. Base oil is recovered and water is further treated if necessary before being released to the recipient.

Typical treatment temperatures lie between 250-300°C. Avoiding an excessively high temperature is critical in preserving the quality of the recovered base oil (Kleppe, 2009).

The capacity of a TCC facility depends on the size of the motor, but a significant proportion of the energy consumption depends on changes in the quantity of water to be converted from the liquid to the gaseous phase. Capacity will accordingly depend on the oil and water content of the cuttings. To maintain stable capacity during treatment, the aim is to keep the dry matter in the cuttings at a high level which is as stable as possible to avoid using more energy than required for vaporisation.

The TCC ® technology will yield three post-treatment end products – water, crushed rock and recovered base oil. The quality of these will depend on various factors, including the type and quality of the base oil used and how the equipment has been maintained. The technology supplier has specified expected quality levels for the end products. See Table 1. These levels will lie between the technology specification and the best results. One of the benefits of using TCC is that it treats the oil carefully, so that this can be recovered for use as base oil in further drilling operations. This recovery solution increases opportunities to achieve profitability with this type of offshore treatment technology for OBM cuttings.

Table 1. Description of the quality of end products after treatment in accordance with the supplier's specification and the best results achieved.

Description	Specification	Best result
Residual oil in treated cuttings (ppm)	<2000	200
Particles in recovered base oil (ppm)	<1000	<20
Boiling point reduction in recovered base oil (°C)	<5	0
Water content in recovered base oil (%)	<1	<0.5
Oil in water phase (ppm)	<1000	<50

Kleppe (2009) discusses the energy requirement for thermal treatment of OBM cuttings and shows that, for standard cuttings with 70 % solids, 15 % water and 15 % oil, 60 % of the energy will be consumed by the water phase, 23 % by the solids and 17 % by the oil phase. He has also studied the quality of base oil after recovery with the Hammermill process. The samples were taken from TWMA at Mongstad and show that the recovered base oil maintains the same good quality, or is even improved along the way.

2.3. Base oil

OBM cuttings are used to a great extent in those cases where the technical properties of WBMs are not good enough.

Base oils have changed considerably over time. SeeTable 2. Requirements for the working environment (health) and the natural environment have had a big influence on quality developments (Aarrestad, 2013).

Table 2. Overview of base oils used for drilling from a historical perspective (Aarrestad, 2013).

Description	Specification	Year
Diesel oil	High content of aromatics High volatility Dries out and irritates the skin	Pre-1984
Mineral oil	HDF 200 Relatively high volatility Lower aromatic content	1995
Mineral oil	EDC 95/11 or equivalent oils Zero aromatics Low volatility	1998
Low-viscosity oils	Sipdrill 2.0 (paraffin) EDC 99 (mineral-oil based) Zero aromatics High volatility	2002

Today's OBMs usually contain a base oil which is a low-aromatic petroleum distillate based on paraffin with a carbon-chain length of C_{18}-C_{22}.

EDC 95-11 is the most widely used base oil, and has been used in the samples included in this project. It is characterised as yellow pursuant to the Norwegian Environment Agency's criteria. EDC 95-11 has ecotoxicity data (HSE data sheet from Total) which show the following levels of toxicity and biodegradability:

- Algae: EC50 >100 000 mg/l for *Skeletonema costatum*
- Crustaceans in the water phase: EC50 >43 000 mg/l for *Acartia tonsa*
- Sediment reworker: EC50 1211 mg/l for *Corophium volutator*
- Biodegradation: 78 %.

Figure 8 shows oil on the shaker.

Figure 8. OBM and OBM cuttings on the shaker. (Photo: Statoil)

Figur 1. Oljebasert boreslam og oljebasert kaks på shaker, (foto fra Statoil).

3. Environmental risk assessment – literature review

3.1. Environmental effects

Cuttings discharged to the sea from offshore installations could affect the marine environment through:

- Particles with THC/PAH/heavy metals staying in the water column or seabed sediments and thereby influencing organisms in both the sediment and the water column
- Oil (THC), PAH, heavy metals and barium (Ba) being discharged to the sea and potentially affecting organisms in the water column and sediment.

In addition to the above-mentioned effects, the method chosen to handle OBM cuttings – whether on land or offshore – will contribute to greenhouse gas emissions because of the energy required to transport, treat and disposing of the cuttings. All handling of cuttings also has a working environment aspect. The importance of the various elements depends on the discharge point (recipient), energy source (electricity, diesel oil or other, and their carbon footprint), operation and discharge point/disposal from land-based facilities, and the risk of discharges related to vessel shipments from field to land.

Comparing offshore discharges of treated OBM cuttings with today's offshore discharges of WBM cuttings is relevant with regard to effects on the marine environment related to the content of THC and priority pollutants. Differences in particle size and morphology mean that effect on the natural environment are more likely to vary.

Discharges/emissions to the natural environment will depend on the treatment efficiency of the actual technology, the choice of energy source (carbon footprint), operational and maintenance procedures and the chosen solution for handling the actual discharge, including the choice of discharge point.

Statoil has implemented a number of internal projects aimed at qualifying technology for treating cuttings with adhered oil on offshore installations. The results of their internal work and studies implemented by the other oil companies were made available to this project.

3.1.1. Effect of dispersed particles in water

Particles which can remain suspended in the water column for a long time have the potential to be deposited as sludge on the seabed or leak and spread prioritypollutants to the water column, either through the release of these compounds to the water column or through ingestion by organisms in the water column. These particles can cause physical damage to the organisms. The particle form of the finer fractions in the cuttings which are deposited as sediments is significant for the environmental effect of the discharges on fish or filter-feeding organisms in the area. Very sharp and angular particles can harm fish gills. Very small particles (< 2 µm) could flocculate and thereby sediment more quickly. Good data on the actual size distributions of particles released to the water column are accordingly important when modelling dispersion in order to assess the consequences of particle discharges.

Sedimentation speed depends primarily on particle size and density, and on current speed in the area. Generally speaking, small particles of < 20 µm will seldom settle on the seabed, while all those > 600 µm will become sediment regardless of the current speed. Figure 9 presents the theoretical relationship between current speed, particle grain size and sedimentation (Hjulström diagram). The lower the current speed, the greater is the sedimentation. The smaller the particles, the more easily they are transported with the current.

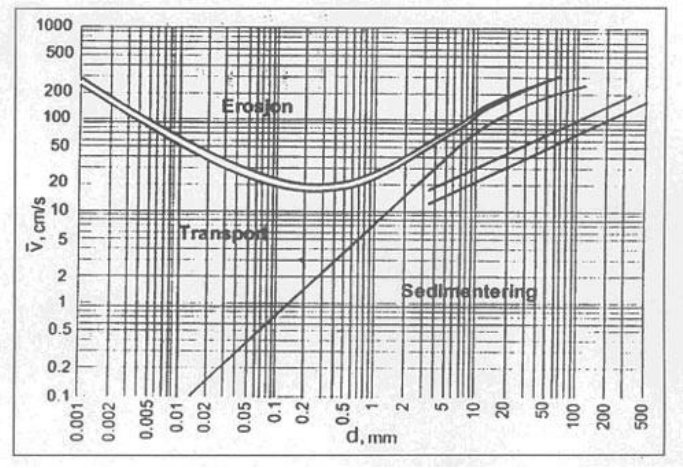


Figure 9. A Hjulström diagram (Selmer Olsen, 1976) showing current speed (cm/s) against grain size (mm) and the areas in which particle transport and sedimentation occur.

3.1.2. Greenhouse gas emissions

In order to compare land- and offshore-based treatment solutions for environmental effects, Statoil has conducted an LCA for greenhouse gas emissions and emissions to the air for the two options. Whether an LCA related to greenhouse gases is the only correct end point for comparing environmental effects when weighing onshore against offshore-based cuttings treatment has therefore been questioned. The LCA has been commissioned by Statoil for Snorre (Hung, 2012), and its results have been discussed in this report and used as one of several input parameters to the environmental risk analysis.

3.2. Environmental effects of discharges of WBM drill cuttings

A report was prepared by Bakke et al (2012) to sum up the results from the research programmes covering long-term effects of discharges to the sea from the petroleum industry (PROOF and PROOFNY). The research institutes which have contributed to these two programmes include the Norwegian Institute for Water Research (NIVA), the International Research Institute of Stavanger (IRIS) and the Norwegian Institute of Marine Research (HI). Findings from the report related to the effects of cuttings discharges are summarised below.

3.2.1. Seabed

Environmental effects from today's WBM discharges were tested in controlled experiments by placing millimetre-thick layers of WBM cuttings on a "natural" sediment community in laboratory trials. A weak impact on recruitment to benthic fauna could be observed. Effects related to higher oxygen and nitrogen consumption were otherwise observed, which suggests an increased content of easily degradable organic substances – including glycol. Effects of sludge deposition or the form and size of cuttings particles were seen when the thickness of the cuttings layer exceeded 10 mm. As a result, effects are not expected more than 250 metres from the discharge point. Since the tests did not cover periods more than a few months long or the repeated exposure which would be typical of production conditions, cumulative effects over a larger area could not be excluded.

3.2.2. Water column

The effects of suspended WBM with barite as the weighting material have also been investigated for the gills of filter-feeding mussels and juvenile cod. More than 0.5 mg/l of suspended WBM caused gill damage in juvenile cod, while 40 mg/l reduced life expectancy after three weeks of exposure. Tests revealed a difference if the drilling fluid was adsorbed to the particles or if the latter consisted solely of barite. The suspension of both particles from

the cuttings and WBM with barite reduced growth and food intake in juvenile cod. The explanation was that the larvae ate cuttings particles without nutritional value. A positive growth effect from exposure to WBM could not be explained. Effects for various mussels were observed for concentrations down to 0.5 mg/l suspended drilling fluid. While other studies concluded that the biological availability of heavy metals in barite is low. Investigations in these programmes show that heavy metals have been taken up from barite via the gut in mussels, scallops and cod. It was concluded that the effects of absorbing heavy metals from suspended WBM suggested physical stress rather than metal toxicity.

The natural level of suspended material in the North Sea is 0.2-0.4 mg/l, and an additional load of 0.15 mg/l could therefore be expected to have effects on the phytoplankton which drifts past. At the same time, physical stress is unlikely to produce cumulative effects in the water column because the same body of water is not subject to the repeated addition of cuttings. The conclusion from the PROOFNY programme is that WBM and cuttings can have biological effects both when suspended in the water column and after sedimentation. The principal effects appear to be physical stress, but oxygen and chemical toxicity could play a role. Cuttings suspended in the water column could have effects at a maximum of one-two km from the discharge point, while the thickness of the cuttings layer on the seabed which is expected to produce effects would be confined to 250 metres from the same point.

The Havkyst research programme run by the Research Council of Norway and the PROOFNY project looked at the effects of oil pollution on *Calanus finmarchicus* (fact sheet, 2009). *Calanus finmarchicus* is a copepod and a significant zooplankton species for the food supply of important fish species such as herring and cod in the North Atlantic ecosystem. It can be found in huge numbers in the total oceanic biomass (70 per cent), which makes the species highly vulnerable if discharges have effects on it. Studies have shown that *Calanus finmarchicus* is fairly tolerant to water-soluble derivatives (WSD) of oil, oil suspensions and water accommodated fractions (WAF) of oil (Brude et al, 2011). These studies have not investigated effects of particles. Since *Calanus finmarchicus* is a filter-feeding organism, particles in the water phase could have negative effects on this species. See Figure 10.

Figure 10. Calanus finmarchicus. (Photo: Dag Altin)

Discharges of particles are important in discharge permits when this is a relevant issue for the ecosystem. For some industries, particle discharges represent a significant consideration in impact assessments and discharge permits, particularly for the discharge and disposal of mining-slag particles in fjords. An enterprise in Sogn og Fjordane, for example, has applied to dispose of four million tonnes of mining slag per annum, including 600 000 tonnes of particles smaller than 20-40 µm. Impact assessments conducted for this activity are considered to involve uncertainties related to the impact of discharging small particles, including dispersion and the effect in the water column. The pollution authorities accordingly recommended that more information should be submitted on this point before they could consider the application (Norwegian Environmental Agency, 2012). By comparison, discharges of treated OBM cuttings from a well will amount to roughly 1 000 tonnes, which will be about 0.17 % of the total quantity of fine particles (< 20-40 µm) planned to be

discharged every year and 0.25 % of the annual total discharge of particles from the Førde Fjord mine.

A number of environmental research projects have been conducted by the oil industry in order to find a methodology which can be used to assess environmental effects from discharges of WBM cuttings. IRIS conducted several studies in the PROOF programme with TNO of the Netherlands and Britain's Plymouth Marine Lab (Bechmann et al, 2007), which aimed to understand the environmental effects of discharged WBM cuttings on organisms living in the water column and on filter-feeding mussels. Procedures were developed which made it possible to test the exposure of the organisms to the smallest particles in the cuttings (the weighting material is used in sizes of 15-20 µm) in order to subsequently analyse whether heavy metals are taken up by the organisms. Various particle analysis methods were used by IRIS, which concluded that the Coulter Counter underestimated the number of small particles and decided to use Malvern for the final documentation of particle composition. The Malvern analysis showed that 14 volume per cent of the particles in the WBM cuttings were < 1.6 µm and 4 volume % were > 50 µm. For barite particles, 6 volume % were < 1.6 µm and 25 volume % were > 50 µm. According to TNO (Smit, personal communication, 2007), the highest measured concentrations of spent WBM cuttings (barite and ilmenite particles) were from 10-50 mg/l and were found in the lowest 10 metres of the water column about 500 metres from the discharge point. Bechmann et al (2007) demonstrated negative impacts at particle concentrations of 0.5-62 mg/l. Queen scallops were the most sensitive, but also cod and blue mussels suffered negative effects. With barium used as the weighting material, the following effects were demonstrated:

- 0.5 mg/l: Ba and copper (Cu) content increased; reduced filtration speed for mussels (*Pecten maximus*); changed protein pattern in plasma/lymphocytes in cod, blue mussels (*Mytilus edulis*) and queen scallops (*Aequipecten opercularis*)
- 2 mg/l (cod exposed to four mg/l because mussels reduced the concentration to two mg/l): significant increase in Ba level in gills and digestive system; significant increase in effects, increased oxidative stress, 40 % reduction in lifespan for mussels, reduced weight of mussel larvae
- 20 mg/l (cod exposed to 39 mg/l): increase in Ba, Cu, lead (Pb) and zinc (Zn), further increase in effects.

The environmental risk management system (ERMS) project determined values for the predicted no effect concentration (PNEC) of the weighting material in cuttings (Smit et al, 2006). A documentation was also conducted using comparative measurement data from fields (Norway's environmental monitoring database – MOD) by comparing two methods – species sensitivity distribution (SSD) and mowing window modelling (MWM) – to arrive at the PNEC (Brakstad et al, 2006). The following PNEC values were calculated.

- Ba from EU's TGD→ PNEC = 0,0032 mg/l
- SSD→ **PNEC**s of **Ba=0,2**; Bentonitt=**0,09**; attapulgitt=**1,8** and WBM cuttings = **0,8 mg/l**

3.2.3. Sediment

A review of monitoring data revealed that the effect on benthic fauna compared with measured concentrations did not agree for barium and heavy metals, and that background values had to be taken into account. Altin et al (2008) have reviewed all the data produced by various research projects, including the ERMS, and recommended applying the principle specified in the EU's TGD (EC, 2003) for arriving at sediment values for the metals. $PNEC_{sediment}$ for metals based on the equilibrium distribution between water phase and sediment agree well with field-specific PNEC values determined by the SSD or MWM methods for all metals with the exception of mercury and chromium. The following PNEC (µg/g dm sediment) values were recommended:

Cd→ 0,04 µg/g dm
Cr→10,08 µg/g dm
Cu→4,13 µg/g dm
Hg→ 0,104 µg/g dm.
Pb→10,9 µg/g dm.
Zn→ 21,16 µg/g dm.

These PNEC values have not been supplemented with background values from unpolluted areas.

The background concentrations found on the NCS (mg/kg sediment measured by dry weight) were as follows:

Ba→ 131 (4.6-554) mg/kg dm
Cr→14.6 (2.58-39.2) mg/kg t.s
Hg→0.021(0.003-0.1) mg/kg t.s.
Zn→20,7 (0.41-83.7) mg/kg t.s.
Cd→ 0,0037 (0,003-0,130) mg/kg
Cu→4.10(0.3-17.2) mg/kg t.s.
Pb→10.7 (1.92-46.5) mg/kg t.s.

Reported background values from the NCS for Ba were 4.6.-554 µg/g dm with a median of 131 µg/g dm. Altin et al noted that PNEC values for Cr and Hg could not observe the same rules as the other heavy metals. Equilibrium considerations between water and sediment can be used for all other heavy metals, and account taken of background values. Altin et al emphasised that greater understanding is needed for these two metals.

The PNEC in the list above differs significantly from the PNEC proposed by the Norwegian Environment Agency for assessing condition classes in coastal waters and sediments (Weideborg et al, 2012). Altin et al (2008) used a barite/water distribution coefficient as the sediment/water distribution coefficient, which is more suitable for describing the fate of metals from cuttings in sediments than the standard distribution coefficient used in Weideborg et al (2012). These values have also been corrected after field observations.

To ensure that environmental risk assessments are consistent with the Norwegian Environment Agency's other assessments of water and sediment, we have used the values from Weideborg et al (2012) in our assessments since these are the latest specified by the Agency:

Cd→ 2,5 µg/g (background value 0.2)
Cr →620 µg/g (background value 60)
Cu→84 µg/g (background value 20)
Hg→ 0,52 µg/g (background value 0,05)
Pb→150 µg/g (background value 25)
Zn→ 90 µg/g (background value 340)

In parallel, we have also made an assessment based on the values in Altin et al (2008), since these could be more suitable for describing the environmental effect of cuttings. The PNEC values used were then supplemented with the background concentration reported in the same article. However, this can vary somewhat from one monitoring region to another.

Higher background values are reported from coastal waters than on the NCS. It is worth noting that Altin et al (2008) also reported large variations in background values – from 0.003-0.130 µg/g dm in sediment for cadmium, for example. On a world basis, Altin et al (2008) reported a variation range in background values for cadmium of 0.1-0.4 µg/g dm.

In our assessment of cuttings and leachate, we have used colour codes which accord with the Norwegian Environment Agency's proposed new values (Weideborg et al, 2012), but have based our PEC/PNEC calculations on values both from the agency and from Altin.

3.2.4. Deepwater organisms

Discharging cuttings in deep water has created concerns about damage to cold-water corals, sponges and the species-rich communities found in such ecosystems. The *Lophelia pertusa* coral species – see figure 11 – has proved capable of removing sludge up to six mm thick,

but not 19 mm. Studies showed no differences if the corals were covered by cuttings sludge or natural sediment (Bakke et al, 2012). Should a covering of sludge remain on the coral, the underlying tissue may be smothered to death. Results suggest that *Lophelia pertusa* is not particularly sensitive to sedimentation by cuttings, which is supported by many discoveries of this species on oil installations where several types of cuttings have been discharged over many years. Environmental monitoring on the Morvin field showed that local currents affected coral behaviour, while the corals did not seem to be affected by smothering from cuttings particles. Nothing is known about how cuttings affect sensitive species on the rich deepwater coral reefs or sponges.

Figure 11. The Lophelia pertusa coral species. (Photo: Tomas Lundälv)

3.3. Treated OBM cuttings

OBM cuttings treated with TCC have been investigated and tested for particle size, morphology, content of priority pollutants and toxicity. The following section provides a summation of the conclusions from these studies.

3.3.1. Characterisation

The Norwegian Institute for Agricultural and Environmental Research (Bioforsk) characterised treated OBM cuttings (Amundsen and Sørheim, 2011). The report does not specify which installation(s) the samples derive from or the type of source material (drilling field and geology). The purpose of the study was to characterise treated cuttings from TCC with a view to their use as soil improvers or filler/building materials. Various samples were taken in the study with different sampling regimes: monthly blend samples (n=23) for heavy metals, THC, PAH16 (n=3) and PCB7 (n=1), weekly blend samples (n=15) for heavy metals, PAH16, cyanide, sulphide, sulphate, phenol index, ammonium, selenium, chlorine and bromide, and random samples (n=60) for PAH16 and THC.

The large number of samples made it possible to obtain a statistical distribution for the various parameters. Variations in the concentration of certain heavy metals were relatively large, which reflected the rock from which the cuttings came. Metals with the largest variations (minimum/maximum) were cadmium from 0.2 to 3 mg/kg dm, lead from 13 to 89 mg/kg dm, barium from 70 to 17 000 mg/kg dm and zinc from 53 to 470 mg/kg dm. The THC content (C_{10}-C_{40}) varied from 73 to 2 600 mg/kg dm in the samples. Total PAH16 content varied from 0.038-3.28 mg/kg dm.

Leaching, shake (LS10) and column (LS0.1) tests have also been conducted. In these leaching tests, Bioforsk compared concentrations of various priority pollutants with known PNECs.

Substances assessed were chlorine, fluorine, sulphate, arsenic, cadmium, chromium, copper, nickel, lead, mercury, antimony, ammonium and all PAH compounds from PAH_{16}.
The conclusion was that a potential for biological effects exists with fluorine, copper and nickel if pore water from the sediment leaches to water (concentrations more than 10 times higher than the PNEC). The content of chlorine, sulphate, arsenic, chromium and ammonium was also above the PNEC values, but to a lesser extent.

PSD in the Bioforsk study showed that particles of cuttings treated by TCC comprise 20-40 % sand (60-2 000 µm), 50-70 % silt (2-63 µm) and 5-15 % clay (< two µm). The percentage distribution is by weight percentage.

Statoil has also investigated OBM cuttings treated with TCC. Results from tests conducted in Statoil's own laboratory and at the Norwegian Geotechnical Institute (NGI) are presented in a note from Aas (2013). This study aimed to provide a general characterisation of treated cuttings, including morphology, element analysis, PSD (volume per cent) and organic content. Statoil considers that the particles are generally very small, with substantial variation in particle size. Thermal gravimetric analysis using a Perkin Elmer TGA7 shows that the cuttings are reduced by about 10 per cent by weight between 300-800°C, but that the weight reduction before that level is minimal.

The content primarily comprises silicon, oxygen and aluminium with traces of magnesium, sodium, calcium, barium, sulphur, iron and chloride.

The PSD shows a maximum of about 150 µm (volume %), but the size distribution indicates that particles generally lie between 100-250 µm. The mean particle size was 108 µm.

TWMA has analysed treated cuttings on various occasions, particularly with regard to PSD. In a test report from Intertek, the PSD (volume %) had been determined in three cuttings samples using a Coulter Counter LS230 laser diffraction particle size analyser. The cuttings were introduced to the machine as a paste containing one per cent dispersant agent (non-ionic surfactant). The sample showed a mean particle size of 20.4 µm. Sizes varied over a large range, from 0.4 to 100 µm.

3.3.2. Life-cycle analysis of treatment offshore versus onshore

LCA (Life Cycle Assessment) is a method for acquiring a holistic view of the total environmental impact of a product during its life cycle from extraction via the production process through application to waste disposal. It includes all transport and all energy consumption in the intermediate stages. This method is used for a defined system to identify particular environmental goals and limitations, and assumptions must therefore be established and defined. Results from an LCA must accordingly be used intelligently, and must also be assessed on the basis of what is realistic in practical and financial terms.

In a PhD thesis, Pettersen (2007) evaluated the drilling process with various muds used offshore, and compared treatment and disposal offshore with onshore treatment. This study utilised LCA and impact assessment. The conclusion drawn was that all cuttings, both WBM and OBM, should be treated onshore. The major contribution to reducing the aquatic ecotoxicological loading (> than 34-40 %) was to treat all types of cuttings, including WBM, onshore. If all cuttings are treated onshore in any event, OBM should replace WBM because the base oil could then be recovered. Such a solution would boost the transport load, which would in turn increase the oil industry's climate effect by 10 per cent.

This study has been criticised by the oil industry because it does not take account of practical, financial or political aspects of offshore waste treatment.

Statoil conducted an LCA which compared the use of offshore thermal treatment of OBM cuttings with the same process applied onshore, and provided an assessment of the environmental impact of the entire life cycle of the treatment process. The LCA included the whole drilling operation and conditions related to energy consumption in all operations "from cradle to grave". It covers a number of environmental issues and sums the environmental consequences of technology design and implementation. The LCA for covered various options for thermo mechanical treatment of OBM cuttings connected to drilling on Snorre. Use of the TCC technology was assessed under the following scenarios.

Offshore Snorre the TCC unit
- Used diesel oil as the energy source
- It was connected to the platform's electricity system

Onshore Oseberg South, the TCC unit
- Had electricity consumption (EU mix)
  - Transport using existing ship traffic (no extra ships needed)
  - Used dedicated ships for transport of the largest quantities of OBM cuttings

The following applied for Snorre:
- Emissions to the air from diesel oil and natural gas, combustion in the turbines on Snorre (NOX, nmVOC, CH_4, SO_X and CO_2)
- Turbine efficiency 35 per cent
- Heavy metals, particles and CO_2 determined on the basis of the amount of fuel used

The LCA assumed:
- Onshore: 50 % recovery of base oil and heavy fuel
- Offshore: installation and demobilisation once per well, discharge of treated cuttings to the sea and recovery of base oil
-

The LCA showed that 82-92 % of all effects are related to the drilling operation, and the rest to whether the cuttings are treated offshore or shipped to land for onshore treatment. The base case for the study was that 50 % of 17½-inch cuttings were sent onshore and the rest are treated offshore (WBM cuttings). Concerning onshore treatment of cuttings, no account was taken to loading cuttings for treatment onshore, worker safety issues and possible increased environmental effects related to preparation of slurry to make be able to pump the cuttings. The LCA does not cover environmental effects related to the discharge of particles, oil, PAH or heavy metals to the sea or issues related to disposal of residual waste onshore. The following conditions were assessed in the LCA:

- Climate change (CO_2 and CH_4)
- Human toxicity (nmVOC)
- Emissions to the air (NO_X, SO_X and particles)
- Terrestrial acidification (SO_X and CO_2)
- Fwater eutrophication (NO_X)
- Marine eutrophication (NO_X).

The results of the Snorre study show that, for this field, the LCA comes out best on shipment of cuttings onshore for treatment if if could be carried by transport by ships in normal traffic (do not require special transport) and hydropower can be used onshore. No account was taken to safety- and worker's health related to loading and discharging the cuttings. Use of diesel oil was assumed offshore, while waste handling and environmental aspects related to discharges to the sea are not assessed. Using diesel oil for offshore treatment of cuttings provides the largest emissions of greenhouse gases and of particles, NO_x and SO_x, and thereby marine eutrophication and terrestrial acidification. The picture changes if the transport of cuttings is carried out by dedicated ships. Emissions of NO_x and particles are then higher with onshore treatment. If electricity can be used offshore, most of the negative

aspects will improve significantly. The distance from a relevant platform to land is also crucial for the outcome of the LCA.

Sending cuttings onshore utilises either open or closed containers. These are transferred from platform to ship by crane, or the cuttings can be pumped or blown across (pneumatic transfer). This is the simplest, cheapest and most flexible method. Where HSE is concerned, risks are associated with crane handling, spillage, weather conditions for the crane lift, cuttings freezing to the substrate and problems with a high ROP. The best approach is therefore to use closed containers while drilling, or pneumatic transfer to the ship.

This LCA did not take account for:

- Discharges to water
- Handling of waste
- Health risk associated with transport, loading, discharging etc. (crane lift, spillage)
- Need for intermediate storage onshore or on the rig.

3.3.3. Carbon footprint

Tracey Elrich (2009) compared the carbon footprint for a mobile TCC unit used offshore with transport to and treatment in a comparable facility onshore. The conclusion was that transport onshore and treatment there would double carbon emissions compared with treating the cuttings offshore. The distance to land in this assessment was 264 kilometres. Diesel oil was used in the facility both offshore and onshore in the first calculation. In the second, electricity was used in both locations. The third assessment also took account of transport by ship. Eight wells were assumed to be drilled during a single operation, and cuttings were expected to be shipped onshore in dedicated vessels.

4. Methods – analytical methods and procedures

4.1. Sampling

Sampling has been carried out in three rounds because activity at the TCC treatment plants was low during the project period. Two rounds of sampling took place in the TWMA plant at Mongstad – see Figure 12 and Figure 13– in January and August respectively, and one at the MI-Swaco plant at Cuxhaven in Germany during June. Aquateam COWI did not take the samples in Germany. Instead, operation's personnel at the plant took them in accordance with for Aquateam COWI's instructions and sent them express to Norway for analysis. Sampling was conducted by Aquateam COWI in collaboration with TWMA personnel at Mongstad on 22 January 2013 and 27 August 2013. The samples from the MI-Swaco plant at Cuxhaven were taken by Damian Unverricht.

Samples of cuttings from wells drilled on the NCS before and after treatment have been taken from different formations and rock types – i.e., shales and carbonates. See Table 3. The samples represent a blend of skips with the same declaration number from the same well, and the three cuttings samples 41, 38 and 17 accordingly represent well lengths of 60, 100 and 100 metres respectively from three formations. We know little about the samples of cuttings from MI-Swaco's Cuxhaven facility, other than that they are blends from different sections in various fields and wells offshore. It is accordingly impossible to specify the rocks these cuttings come from. Formation oil could reportedly be included in these samples. We were sent a sample of the mud used during drilling from Germany.

The samples taken after treatment were very hot and had to be cooled down before they could be transferred to packaging. Rilsan bags were used for sample packaging, and the samples were stored in a refrigerator (0-5°C) until they could be prepared and analysed.

Table 3. Sampling of OBM cuttings – sample information.

Declaration number	12¼-inch section depth (m)	Formation group	Formation name	Rock type	Sample ID	Date	Facility
8836641 (**41**)	1 935-1 957	Rogaland	Lista	Shales 12¼-inch	In 41 out 41	22/1	Mongstad
	1 957-1 977						
	1 977-1 996						
8836638 (**38**)	2 129-2 158	Shetland	Svarte	Carbonate 12¼-inch	In 38 Out 38	22/1	Mongstad
	2 158-2 205						
	2 205-2 226	Cromer Knoll	Rødby				
Unknown (**C**)	Unknown	Unknown	Unknown	Unknown	In C Out C	1/7	Cuxhaven
*CMHU000017 and IPO 327 (**17**)	1 664-1 712 Unknown	Hordaland	Brynhild field	Shales with dolomite elements 17½-inch	In 17 Out 17	27/8	Mongstad

* Two tanks of 40 tonnes and 24 m^3 in total contained OBM cuttings for treatment from the 17½-inch well section. The total well length for the two containers of cuttings is calculated to be about 100 m.

Figure 12 presents photographs of the sampling at Mongstad in January (samples 41 and 38, in and out of the TCC facility). Figure 13 presents photographs of collecting samples from the TCC plant (In 17) in August. The TWMA indicated that the original cuttings were too thick for the feed pump to operate correctly, so that a small quantity of oil recovered from the

cuttings was recycled to dilute the sample. Samples of both original and diluted cuttings were taken (Figure 13). The original cuttings for treatment comprised about 20 per cent water, 20 per cent oil and 60 per cent dry matter, which became 28, 26 and 46 per cent respectively after dilution.

The TCC process at Mongstad was run at 275°C with a capacity to handle two tonnes of cuttings per hour. Samples of treated cuttings were taken at the outlet of the facility from the transport screw immediately downstream from the mill by TWMA's personnel (figure 14). The solid matter (Out 17) was collected in a stainless steel bucket and cooled for about two hours before being transferred to the sample bag (Figure 14).

Hot treated cuttings are mixed with water for cooling at Mongstad, and the water is then removed before final disposal.

Figure 12. Sampling untreated (carbonate In 38) and treated OBM cuttings (carbonate Out 38) in the TWMA facility at Mongstad in January 2013.

Original cuttings Cuttings diluted with recycled oil

Figure 13. Sampling original cuttings at Mongstad in August 2013.

Figure 14. Sampling treated cuttings (Out 17), cooling the sample and treated cuttings ready for disposal. Mongstad in August 2013.

4.2. Sample preparation

4.2.1. For PSD analyses (In samples)

Untreated samples of cuttings (In samples) were sticky and oily, with a waxy texture. They were examined under a microscope and photographed. See Figure 15. The treated samples (Out samples) contained significantly smaller quantities of oil and were more like a fine powder than the in samples. The following procedure was followed to prepare the In samples for determining the PSD:

- A known quantity was weighed into a 500 ml Duran flask
- H_2O was added to the 400 ml mark
- The sample was heated to 60°C for 30 minutes
- 100 µm of emulsion breaker (EB) was added to each sample, which was then vigorously shaken
- The sample was re-heated to 60°C for 60 minutes, followed by vigorous shaking
- 25 ml of cyclopentane (CP) had to be added to samples In 38 and In 41 in order to remove the oil so that the samples could be used to determine the PSD. The samples were left overnight for sedimentation to occur. This was not necessary for samples In 17 and In C.

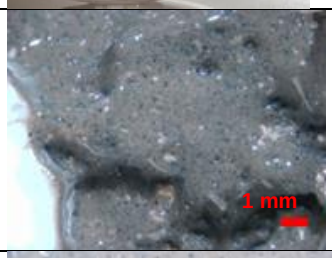
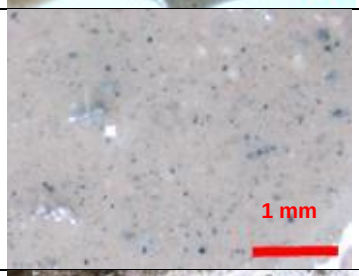
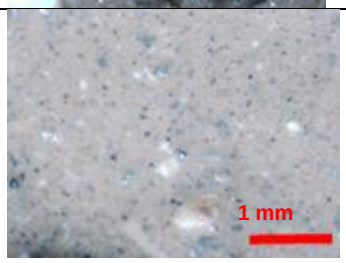
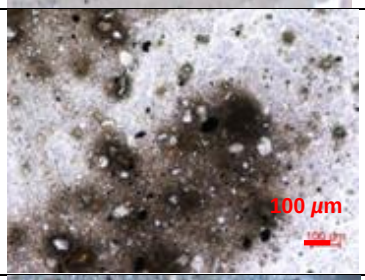
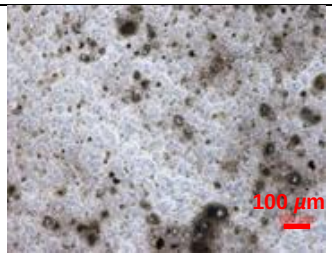
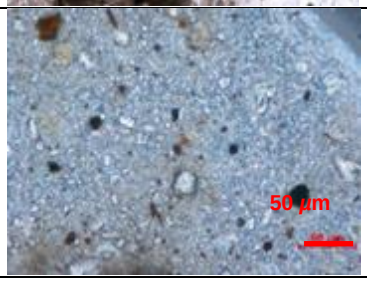
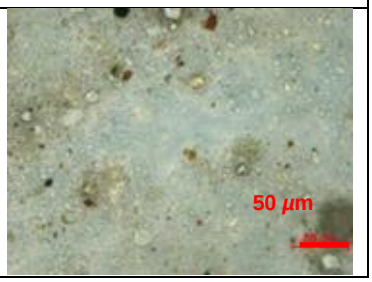
Samples	In 38	In 41
Untreated cuttings		
Doubling of magnification under the microscope (magnifying glass)		
Doubling of magnification under the microscope (magnifying glass)		
High resolution microscope. Red line 100 µm		
High resolution microscope, increased magnification. Red line 50 µm		

Figure 15. Microscopic examination of untreated OBM cuttings at various magnifications. The red line indicates 50 µm, 100 µm and one mm in order to show the scale.

Figure 16 presents the preparatory stages for samples In 38 and In 41. Untreated cuttings behaved like “chewing gum” when they came into contact with water, and formed a lump in the bottom of the flask.

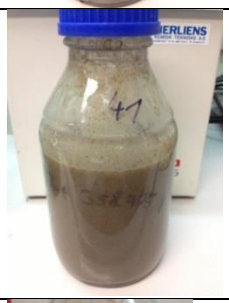
Samples	In 38	In 41	
After addition of EB and heating			Both samples were sticky, and large quantities of cuttings stuck to the walls of the flask
During cooling and initial sedimentation			Cuttings loosened from the flask wall and particles suspended in the liquid. Separation and sedimentation of the particles began after this
After overnight sedimentation			A thin phase of organic matter and a thin layer of sediment lay on the bottom and floated on the top of each flask

Figure 16. The appearance of untreated cuttings during sample preparation.

4.2.2. Physical/chemical analyses

The samples were well-blended before taking sub-samples. Sub-samples of the In and Out samples were analysed for total dry matter (DM), volatile dry matter (VDM), grain distribution (weight per cent), PSD and all chemical analyses (PAH, THC, heavy metals). DM/VDM were analysed pursuant to Norwegian Standard NS 4764. Sub-samples of the Out samples were also analysed with a scanning electron microscope (SEM) in Statoil's laboratory. DM will contain all particulate material, including oil. VDM includes all organic solids and possible carbonate, which are burnt off at 500°C.

Total suspended solids (TSS) and volatile suspended solids (VSS) in Out samples 38 and 41 were determined from a one g/l solution. The analysis has been used to calculate the quantity which should be added for PSD (volume per cent) and microscopy studies. The TSS/VSS analysis has been conducted pursuant to Norwegian Standard NS 4733. The water samples are filtered using a 1.2 µm GF/C filter, which is dried and heated to a high temperature with weighing between each stage.

A quick test to determine the content of carbonate rock was conducted by adding five ml of 6M hydrochloric acid (HCl) to samples of treated cuttings blended with a little water (one g/20 ml). Gas development was considerable from samples 38 and 41, but limited from 17 and the German samples. Sample 38 was carbonate rock, so this result was expected. Sample 41 came from a layer of shale, but the result indicated that carbonate rock was also present there.

4.2.3. Leaching tests for toxicity testing and chemical composition

Leaching tests were conducted with samples from treated cuttings pursuant to NS-EN 12457-2 (2003). Treated cuttings and liquid (seawater) were blended in the proportion of 10 l/kg and shaken for 24 hours, followed by filtration through an 0.45 µm membrane filter. In this test, 350 grams of treated cuttings were sludged in 3.5 litres of water. The test was modified because of the large quantity of suspended solids after shaking. The sample was therefore left to stand for sedimentation for one day (24 hours) to avoid the filter becoming clogged immediately. See Figure 17. The sample water (filtrate) was sent to be analysed for heavy metals as well as Ba, THC and PAH_{16}, and to be used for ecotoxicity tests with the exception of *Corophium* and *Calanus finmarchicus*.

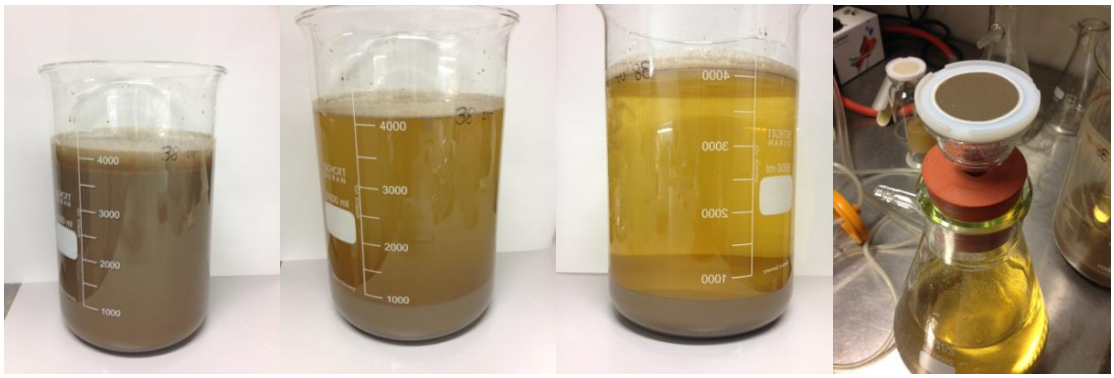


Figure 17. Leaching test. The samples were left to stand for 24 hours before filtration because of large quantities of suspended solids. The photographs show the sample after one minute, 12 hours and 24 hours, and the filter after filtration.

4.2.4. *Calanus finmarchicus* testing

It was agreed with Biotrix that the *Calanus finmarchicus* test would be conducted both with dissolved fractions and with particles present.

This was conducted as outlined below, but all exposure solutions were prepared in duplicate, with one solution filtered through a fibreglass filter (GF/C or similar) to eliminate grazeable particles before exposure in order to look at the possible effects of dissolved compounds isolated from particles. Exposure was conducted in the same way as for corresponding solutions with particles present.

This is conducted as a static test where the test substance is blended with seawater over 20-24 hours in order to achieve an approximate distribution of substances between water phase and particles before the solution is re-suspended and sedimented for a specified period. The supernatant is then decanted and characterised in a particle counter to ensure that the particle suspension is within the grazeable range for *Calanus finmarchicus* (larger than five microns) before being used as the exposure solution. Since exposure is conducted statically in 500 ml glass flasks, these were turned twice a day to bring the particles into suspension. The aim is to conduct the exposure with a nominal quantity of test material, in the interval of one to 20 grams of test material per litre. Data on what this will correspond to in terms of the quantity of grazeable particles after sedimentation will not be available until the test solutions have been prepared and characterised. The exposure is conducted using solutions with six different levels of test material in three parallels for each level and controls in six parallels.

4.2.5. Sedimentation tests

A series of sedimentation tests was conducted with all four Out samples at our laboratory. No standard has been established for conducting sedimentation tests. Van Olphen (1963) states that issues related to the ability of clay particles to flocculate into agglomerations which

increase sedimentation speed is particularly important when the particles come into contact with salt water. He provides the example of river water containing clay particles meeting seawater. This sharply increases sedimentation speed. Our tests have been conducted to help us form a picture of how fast particles from a discharge of thermal-treated cuttings will sediment and what quantities and size distributions of particles will be left in the water column at different times after the discharge. The particles will be discharged to the sea, and seawater has accordingly been used for all the tests. Normally, sedimentation speed for particles is said to be governed by two different laws:

1) Stokes' law applies for small particles – $W1=(d^2 \bullet g')/18U$ where W1 = laminar Stokes sedimentation speed; diameter of particles is d; U is kinematic viscosity (which for seawater is $1.358 * 10^{-6}$ sq.m/s at 10°C); g' is reduced density = $g' \rho_{particle} - \rho_{water})/\rho_{water}$.
2) Friction, which applies to large particles and is dominated by the law of falling bodies: $W_2=\sqrt{[(4dg')/(3C_D)]}$. A general expression is that this sedimentation speed can be derived from the balance between the bending and drag forces acting on the particle. C_D = the constant rate of descent, which is a function of the Reynolds number (Re=W2*d/v).

On the basis of these equations, it can be seen that:

1) Stokes' law dominates when Re <1 and is then $W_1=(d^2 \bullet g')/18v$
2) The falling bodies law (sedimentation) applies when Re> 1 000 and is then $W_2=K*\sqrt{(dg')}$ where K is an empirical dimensionless constant.
3) In the intermediate area, where Re is between 1 and 1 000, the following equation is derived: $W = [1/(1/W_1 + 1/W_2)]$.

Ditlevsen and Daae (2012) describe the models used for sedimentation speed in the Dream model. These correspond with the theory presented above, and results for discharges of dry matter from TWMA are summarised in Figure 18.

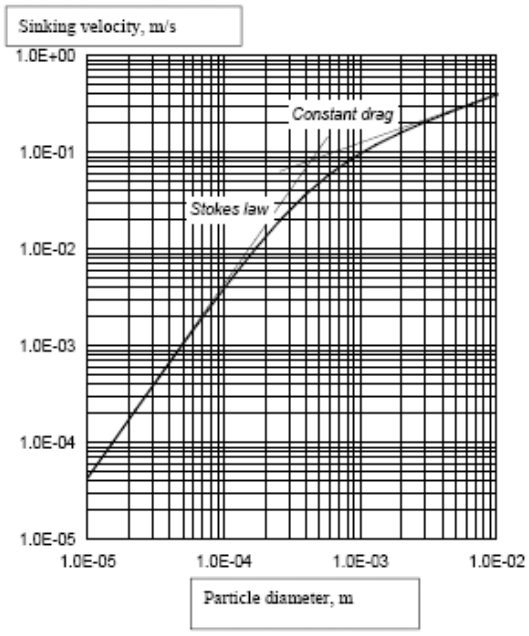
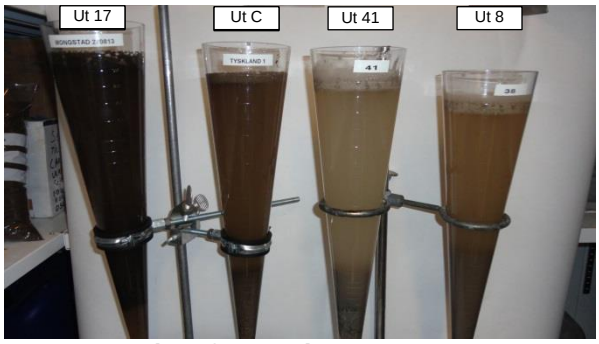


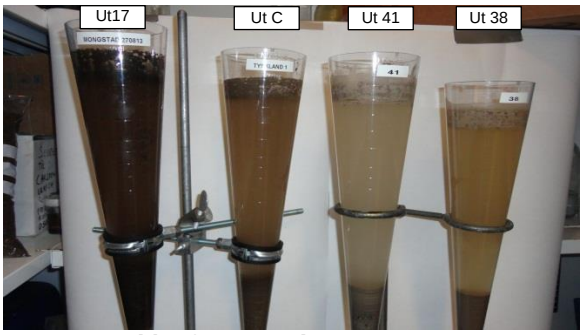
Figure 18. Sedimentation speed as a function of the size of mineral particles in seawater. A density of 2.5 kg/l has been used for the particles (safety data sheet TWMA dry matter, 2012). Thin lines: Stokes' law and law of falling bodies. Thick line = interpolated data.

All the sedimentation tests we performed were conducted by adding 50 grams of sample to 950 ml of synthetic seawater (34 ‰). The samples were shaken up and then left for

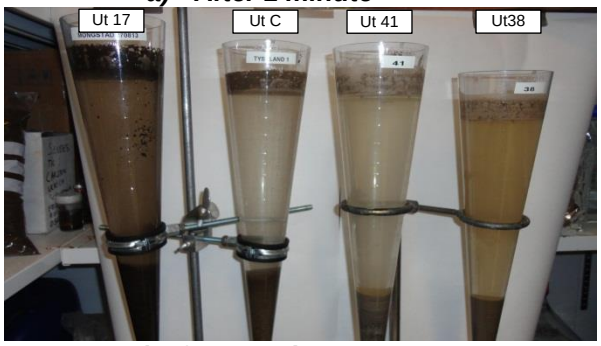
sedimentation. The samples were taken from the sample container with a pipette. The first was taken after one minute, with subsequent samples taken at three, 10 and 60 minutes, at 24 hours and finally at 72 hours. The pipette was inserted a distance of 10 cm into the sample, and 10 ml was extracted. A layer of scum had formed on the top and it was observed that particles fell from this scum layer into the sample during the removal of samples. Samples were extracted for various analyses at different times – for sedimentation: after one, three, 10 and 60 minutes and 72 hours of sedimentation. In addition to analyses conducted in our laboratory, a set of samples was also extracted from the In samples after three minutes of sedimentation and sent to Statoil's laboratory for environmental SEM analysis. The entire report from Statoil is included in the appendix to this report, but the results are summarised and discussed in the main report. The tests were conducted at 4°C (representative for deep water). Sedimentation speed is slower at lower temperatures than at higher. Figure 19 shows the test setup. Conical one-litre Imhoff flasks were used, to which 950 ml of seawater (33 ‰) was added. We regard this simple test setup as representative on the assumption current speeds are very low.



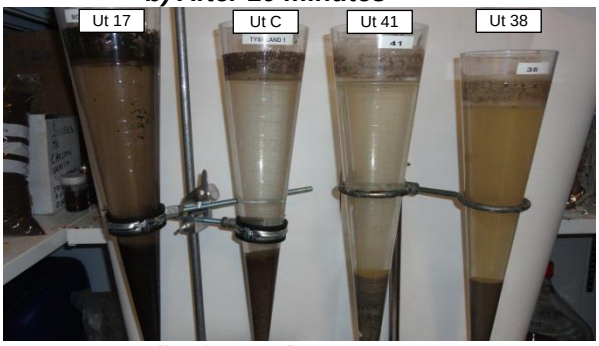
a) After 1 minute



b) After 10 minutes



c) After 60 min



d) After 24 hours

e) Sample 41 after 1 min; 3 min; 60 min og 72 hours

Key: Ut = Out

Figure 19. Sedimentation tests for discharge of TCC-treated OBM cuttings. The photograph series a-d shows all four samples after one, 10 and 60 minutes and after 24 hours. Series e shows the corresponding sequence for sample 41, but after sedimentation for one, 10 and 60 minutes and 72 hours.

4.3. Analyses

Sample material and pore water from the leaching test were sent to Eurofins for chemical analysis of priority pollutants and PSD, and to Clariant in Bergen and BioTrix in Trondheim for ecotoxicity analyses, see Table 4. We conducted leaching tests to acquire pore water for analyse and selected ecotoxicity tests. The Microtox and *Corophium* ecotoxicity tests have been conducted by Clariant and BioTrix. *Calanus finmarchicus* has been tested at BioTrix. Aquateam COWI conducted ecotoxicity tests with *Acartia, Skeletonema* and Mara, analyses of PSD and microscopy, and the physical/chemical analyses.

Table 4. Overview of the analysis programme for cuttings samples. In and out represent samples before and after thermal treatment respectively. Pore water has been acquired from the leaching tests with treated cuttings.

Analysis	Chemical	Physical	Ecotoxicity[1]	Laboratory
PAH16	In, Out and pore water		Out samples Pore water	Eurofins
Heavy metals + Ba	In, Out and pore water			Eurofins
THC C_{5-35}	In, Out and pore water			Eurofins
PSD		Out and In samples		Eurofins and Aquateam
Morphological description		Out and In samples		Aquateam
Sedimentation test		Out samples		Aquateam
Microtox			Pore water	Clariant
Chorophium volutator		Out samples	Sediment	Clariant/BioTrix
Calanus finmarchicus			Pore water with and without particles	BioTrix
Acartia tonsa			Pore water	Clariant
Skeletonema costatum			Pore water	Aquateam
Mara			Pore water	Aquateam

[1] Conducted on Out samples.

4.3.1. Chemical analyses

The sample material of untreated and treated cuttings has been sent to Eurofins, an external laboratory, for chemical analysis of PAH_{16}, heavy metals, barium and THC fractioning from $<C_5$-C_8, C_8-C_{10}, C_{10}-C_{12}, C_{12}-C_{16} and C_{16}-C_{35}. The methods used as well as detection limits and uncertainty are specified in Table 5. LOQ = Limit Of Quantification.

Table 5. Information of LOQ limit for the analyses and uncertainties in the analytical results.

Analytical parameters		Solids		Liquids		Method
		LOQ*	Uncertainty	LOQ*	Uncertainty	
		mg/kg dm	%	µg/l	%	
THC	C5-8 C8-10 C10-12 C16-35 C12-16 SUM	5 5 5 5 20	25-30		30	ISO/DIS 16703-Mod
PAH_{16}	Naphthalene Acenaphthylene Acenaphthene Fluorine Phenanthrene Anthracene Fluoranthene	0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005	40	0.01 0.01 0.01 0.01 0.01 0.01 0.01	30-40	Anon 1982 – internal KG.58

	Pyrene Benzo[a]anthracene Chrysene, benzo [b,j,k] Fluoranthene Benzo[a]pyrene Indeno[1,2,3-cd]pyrene Dibenzo [a,h]anthracene Benzo[ghi]perylene	0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005		0.01 0.01 0.01 0.01 0.01 0.002 0.01 0.002		
Heavy metals + arsenic and barium	Arsenic Barium Lead Cadmium Copper Chromium Mercury Nickel Zink	0.02 0.5 0.5 0.01 0.8 0.3 0.001 1 10	25-30	1 1 0.2 0.2 0.3 1 0.05 2 2	Not specified	NS EN ISO 17294-2, For Hg NS-EN ISO 12846, For Ba: NS EN ISO 11885
DM	Dry matter	0.02	12			

* LOQ = limit of quantification.

4.3.2. Physical analyses – morphology and PSD

Eurofins has analysed the PSD with the aid of the pipette method. PSD with laser diffraction and for morphological determination has been conducted by Aquateam COWI. The following physical analyses have been carried out:

- Pipette method and sieving for particles from 2-0.002 (Norwegian standard N-EN 5752)
- Laser diffraction: Malvern Mastersizer – sample measured in a chamber where particle size is calculated on the basis on reflection and sorption of light (laser diffraction) and the volume percentage determined for various particle sizes from 0.5-1 000 µm
- Image analyser- Microscopy and morphology determination – FlowCam
- TSS/VSS, turbidity and PSD in sedimentation tests
- dm and vm (volatile matter) from untreated and treated cuttings.

Determining PSD with the pipette method (g/l) is based on the change in quantity of a sludge sample over time, where the quantitative relationship between particles and water changes because particles of differing size sink at different speeds on the basis of Stokes' law.

Stokes' law: $V = \frac{d^2(\rho_s-\rho_w)g}{18\mu}$

Reynolds number: $Re = \frac{\rho_w V d}{\mu}$

V = the speed of the particle in water
d = particle diameter
ρ_s = particle density
ρ_w = liquid density
μ = dynamic viscosity of the liquid

Stokes' law applies for laminar currents around the particle, and the criterion for this is that the Reynolds number (Re) is below a certain limit. Particles larger than 0.1 mm involve too much speed and turbulence, and their calculated rate of descent is thereby too high. Particles larger than 63 µm to two mm are therefore wet-sieved (sand fraction). The hydrometer method is applied by pre-treating the sample to remove organic material with the aid of H_2O_2 and by adding dispersants (currently pyrophosphate or Calgon) or possibly using

ultrasonics. The dispersant is intended to ensure than the sample contains only primary particles. If the sample contains too many particles, the calculation formula will fail to give the right result.

Particle analysis was conducted in Aquateam COWI's laboratory with a Malvern Mastersizer (300 RF lens). Based on laser diffraction, Malvern measures particles in the 0.5-900 µm size range. To ensure that the particles remained in suspension, a magnetic stirrer cell was used during the measurements. The latter were conducted with a sample volume of 15 ml. The sample is prepared in a concentration which is neither too high nor too low. The analysis is based on a calculation of particle size which depends on the diffraction of light when it hits the particle. The results are provided as a volume percentage of particles in various size ranges.

In addition, we also analysed PSD with FlowCam, which is based on microscopy. The morphological properties of the particles are also determined here.

Statoil has studied the four treated samples with the aid of scanning electron microscopy (SEM). Original treated samples and samples after three minutes of sedimentation have been investigated. In addition, an energy dispersive system (EDS) was used for element analysis.

Different methods for PSD will not necessarily yield the same results. Understanding the methods used is important. Dispersants are not used in the Malvern Mastersizer or FlowCam analyses.

4.3.3. Ecotoxicological analyses

The following toxicity tests were conducted with treated cuttings (the four Out samples).

On leachate:

- Bacteria: Mara (bacteria test, 11 bacterial species); Microtox
- Algae in seawater: *Skeletonema costatum,* acute 72 hours
- Crustaceans: *Acartia tonsa*, acute 48-hour test
- *Calanus finmarchicus* (copeod), acute 96 hours

On sediment:

- Sediment-dwelling organisms: *Corophium volutator*, 10 days

On particles in the water column:

- Filter-feeding organisms: *Calanus finmarchicus* (copeod)

Mara

Microbial array for risk assessment (Mara) from NCIMB Ltd is a biological test comprising a number of bacterial species. The advantage of Mara is that 11 bacterial species are tested simultaneously (Gabrielson et al, 2003). The test organisms are a blend of fresh, briny and salt water species. An intra-laboratory assessment has been conducted with Mara for potential implementation in connection with the water framework directive (Wadhia et al, 2007), where it was tested with many different environmental samples. The results show that the Mara species gave comparable results with Microtox, invertebrates (*Daphnia magna* and *Thamnocephalus platyurus*), microbiological tests, and respiration and nitrification inhibition tests.

Microtox

Screening bacterial test with briny water species *Vibrio fischeri*. It measures toxicity and takes 15 minutes. The bacterium is tested pursuant to Microtox (1992).

Skeletonema costatum
Skeletonema costatum is a marine alga, and the toxicity test includes measurement of growth inhibition over a 72-hour period. Various concentrations of leachate were tested, and the dose response curve plotted. Since *Skeletonema* is a marine alga, the samples were salted up to normal seawater salinity and pH-adjusted to 7.2 pursuant to the test standard (ISO 10253) before testing.

Acartia tonsa
Acartia tonsa is a marine crustacean, and the toxicity test includes measurement of mortality over a 48-hour period. Various concentrations of leachate were tested, and the dose response curve plotted. Since *Acartia* is a marine crustacean, the samples were salted up to normal seawater salinity and pH-adjusted to 7.2 pursuant to the test standard (ISO 14669) before testing.

Corophium volutator
Corophium volutator is a marine sediment-dwelling crustacean, and the toxicity test includes measurement of mortality over a 10-day period. Various concentrations of cuttings in the sediment were tested, and the dose response curve plotted. The test followed the standard guideline (Ospar 2005).

Calanus finmarchicus
Calanus finmarchicus is a copeod species in the order Calanoida, which forms one of the most important links in marine food chains. It has been chosen because it is a filter-feeding organism and can therefore be affected by particles in the water phase. To test possible effects on this species, various concentrations of treated cuttings in suspension were tested over a 96-hour period. The dose response curve was plotted. Since *Calanus finmarchicus* is a marine crustacean, the samples were salted up to normal seawater salinity and pH-adjusted to 7.2 pursuant to the test standard before testing. The test is based on a modification of the ISO standard (1999). With the high particle load, the organisms are tested for the suspended fraction of particles which were present in the supernatant after 20 hours of mixing in a turret mixer at one rpm, followed by four hours of sedimentation before the blend was shaken manually and given another six minutes of sedimentation. The final sedimentation was conducted to remove the largest particles from the solution, which must be regarded as being minimally grazeable by the organisms and which will not contribute appreciably to fouling. With the low particle load, the organisms were tested in solutions prepared in the corresponding way as with the high particle load, but the solutions were sedimenting for 28 hours before the supernatant was decanted or siphoned off and filtered through a fibreglass filter using water suction. To re-establish gas equilibrium in the solutions, they were aerated for 25 minutes with an aquarium pump before being distributed to the exposure flask.

4.4. Environmental risk assessment

4.4.1. General principles

Conducting environmental risk assessment for a substance involves comparing the calculated PNEC limit and the predicted environmental concentration (PEC) of the substance. The PEC/PNEC is the mathematical expression of the environmental risk. Should the relationship have a value greater than one, the risk associated with the discharges could be unacceptable. At a PEC/PNEC < one, the risk of environmental effects is regarded as tolerable. Conducting an environmental risk assessment of a substance requires specific information on chemicals, on concentrations in the discharge, on discharge conditions and on the associated recipient.

Where concentration values have been measured in the discharge, they are used as the base concentration for the PEC. Where this has not been done, calculated values based on quantities released are used. Industrial waste water often contains a number of unknown substances which can have toxic effects, and combinations of different compounds in the discharge can have toxic effects. As a result, normal practice is to specify the PEC as a percentage of waste water. The PEC also takes account of dilution in the recipient. Using a standard dilution factor of 100 for the discharge area is recommended when discharging waste water to the marine environment, for example (technical guidance document, EU, 2003). Since cuttings are solids, we have chosen to take account of the toxicity both of the substance in sediment and of the leachate. A dilution factor of 1 000 will be used for leachate when estimating its concentration in the environment.

The PNEC can be calculated on the basis of all available test results for a substance. Results from standardised ecotoxicological - ideally chronic – tests are used as PNEC values. The result for the most sensitive organism tested is used here, plus a safety factor which takes account of the existence of organisms which are more sensitive than those used in laboratory tests. Generally speaking, the larger the number of organisms tested, the lower the safety factor will be. It will be high if results are only available from acute toxicity tests ($L(E)C_{50}$ values) and chronic data are lacking. Safety factors of 1 000 for discharges to fresh water and 10 000 to seawater were used earlier, but The Norwegian Environmental Agency (NEA) adjusted the one for seawater so that the maximum safety factor for discharges to seawater of chemicals tested in a harmonised offshore chemical notification format (HOCNF) is also 1 000 (Norwegian Environmental Agency, 2013). The EU has detailed procedures for calculating the PNEC (technical guidance document, EU, 2003).

The PNEC can be calculated for different environments, as the following examples show:

- $PNEC_{freshwater}$ is based on tests with freshwater organisms.
- $PNEC_{seawater}$ should ideally be based on tests with marine organisms, but can be calculated on the basis of $PNEC_{freshwater}$ where marine data are lacking. An extra safety factor is included here.
- $PNEC_{sediment}$ should ideally be based on tests with sediment-dwelling organisms, but can be calculated on the basis of $PNEC_{freshwater}$ where sediment data are lacking. The substance's sediment/water distribution coefficient is used in the calculation.
- $PNEC_{soil}$ should ideally be based on tests with sediment-dwelling organisms, but can be calculated on the basis of $PNEC_{freshwater}$ for substances where data from tests with soil-dwelling organisms are lacking. The substance's soil/water distribution coefficient is used in the calculation.
- $PNEC_{microorganisms}$ is based on tests with waste sludge from biological treatment plants.

According to the EU (2003), risk assessments for sediment must be conducted with substances which have log K_{ow}>3 or K_{ow}> 1 000 l/kg. When discharging thermal treated OBM cuttings, this will apply in part to discharges of oil and PAH adsorbed by particles which are released and which will sediment (bentonite, carbonates, barite etc.). Oil and PAH could therefore end up in the sediment together with heavy metals, for example, contained in the particles.

4.4.2. Risk assessment of pollutants leached from cuttings to water

Two methods are used when assessing the acute toxicity of leachate:

1) Theoretical assessment based on the measured concentration of priority pollutants in the leachate and the known toxicity of the relevant substances
2) Measured ecotoxicity of the leachate, $L(E)C_{50}$, specified as percentage of the leachate.

The results of the two methods are compared in order to check that account has been taken of the most important substances in the environmental risk assessments. Where water with a blend of different substances is concerned, the toxicity unit (TU = PEC/L(E)C_{50}) for each substance is used to judge the overall toxicity of the discharge. The TU value specifies the dilution of the waste water required to reduce toxicity to L(E)C_{50} for the relevant toxicity test. Based on the NEA (Norwegian Environmental Agency, 2000), the effect of the various toxic substances are assumed to be additive. The TU for each substance in the blend is summed to find the TU for the blend (TU_{blend}):

$$TU_{blend} = TU_{substance\ 1} + TU_{substance\ 2} + TU_{substance3} +, +$$

The toxicity of the leachate is then $100/TU_{blend}$ = volume per cent.

Such a calculation is made, and the calculated values thereafter checked against the measured toxicity of the leachate. Should the theoretically calculated toxicity accord well with the measured value for the leachate, the most important components in the waste water which contribute to toxicity will have been identified.

The Swedish Environmental Protection Agency (1996) classifies industrial discharges for toxicity as follows:

Low toxicity: L(E)C_{50} is > 70 volume per cent
High toxicity: L(E)C_{50} is < 10 volume per cent

In addition, an environmental risk assessment is conducted on the basis of calculated PEC/PNEC for the individual components in waste water. This is based on the measured concentration (PEC) and calculated PNEC for the known substances, as described in section 4.5.1. An environmental risk assessment of this kind takes account of chronic toxicity and available information on each substance's behaviour in the recipient under assessment. The environmental risk from discharging various substances is assessed as follows:

PEC/PNEC <1: no toxic effect
PEC/PNEC >1: toxic effect.

Calculating the possible dilution required to eliminate any toxic effect of the overall discharge on marine organisms is based on the highest PEC/PNEC value. Dilution of the discharge must be taken into account in such a calculation.

4.4.3. Risk assessment of cuttings particles in water column and sediment

The form of particles in the cuttings being discharged is significant for the environmental effect these discharges could have on fish and other organisms in the area. Very sharp and angular particles can damage fish gills. The samples were accordingly investigated with FlowCam and photographed.

A high content of particulates could have a negative impact on fish and benthic organisms in the following ways:

- Kill the organisms (lethal concentrations)
- Reduce the organisms' competitiveness, inhibit their growth, cause illnesses, prevent or slow the development of eggs and fry (sub-lethal concentrations)
- Negative influence on behaviour
- Reduce available nutrition
- Reduce fish catches.

Particles can kill fish and benthic organisms by inflicting physical injuries. Fish normally tolerate high concentrations of suspended solids over a long period when the particles do not harm their gills. However, fatal injuries have been identified in fish at particle concentrations lower than 25 mg SS/l when the particles are thin and sharp (as after blasting). Sharp and pointed particles can damage gills. Particles can also block the gills and inhibit their functioning. The negative effect of discharging the material could be greater at times when fish are migrating and spawning than in other seasons.

Older guideline values for the quantity of particles (naturally eroded materials) fish can tolerate are provided by the European Inland Fisheries Advisory Commission (EIFAC, 1965) and shown in Table 6. These values refer to natural particles eroded from agricultural land and river banks. They are specified for effects on fish yields and therefore cannot be used to estimate sub-lethal damage. Nor are they related to fish species. It is also assumed that particles from artificial working of stone will have greater negative effects than those from natural erosion. Little documentation is available which makes it possible to set upper limits for the particle concentration in water which affects fish. Colt and Orwics (1991) provide a temporary recommended maximum of 12 mg SS/l.

Table 6. EIFAC's guideline values for the effects on fishing of different concentrations of particles in the form of naturally eroded materials (EIFAC, 1965).

Suspended solids (mg SS/l)	Effect on fishing
< 25 mg/l	No harmful effect
25-80 mg/l	Good to medium-good fishing. No reduced yield
80-400 mg/l	Substantial reduced fishing
> 400 mg/l	Very poor fishing, big reduction in yield

Experience with discharges of particles to rivers in connection with road and tunnel construction has shown that fish normally avoid on area during periods with visible discharges.

To conduct an environmental risk assessment of discharges of thermal treated OBM cuttings with regard to sediment-dwelling organisms and to fish and filter-feeding organisms in the water column, it is necessary to have some knowledge of expected concentration of particles likely to be found in the water column and the quantities of cuttings likely to be found on the seabed after a discharge from drilling a well.

Cordah (2005) has modelled the spreading of the discharged crushed cuttings after offshore treatment with the TCC technology, which shows a maximum sediment thickness of 5.5 µm from the discharge of 177 m^3 at a depth of five metres beneath the sea surface over a 10-day period. Cordah did not model the concentration of particles in the water phase.

Logging by Graham (2010) of discharges from a drilling operation by Total on the UKCS where thermal treatment with the TCC technology was conducted showed that, when OBM cuttings from three different sections – 17½ inches (2 875 metres, 696 tonnes of cuttings), 12¼ inches (933 metres, 511 tonnes of cuttings) and 8½ inches (295 metres, 18 tonnes of cuttings) – were treated, considerably larger quantities of cuttings were discharged to the sea than those used in the modelling conducted by Cordah. TWMA has reported the density of the cuttings to be 2.5 tonnes/m^3, and the total quantity of thermal treated cuttings discharged was 1 060 tonnes compared with the 442 tonnes used in Cordah's modelling.

Det Norske has commissioned SINTEF to model the spread of WBM and thermal treated OBM cuttings discharged to the sea from the Draupne (Ivar Aasen) field during the drilling of a complete well. Ditlevsen and Daae (2012) modelled the spread of WBM cuttings and OBM cuttings Thermal treated in a rotormill. This modelling was based on the assumption that

WBM cuttings came from the top sections (36 and 22 inches) and that OBM cuttings were produced from the deeper sections (17½, 12¼ and 8½ inches).

Drilling an exploration well normally takes two-three months. In practice, however, drilling (or discharge) ceases for long periods because of other activities. The simulation carried out by SINTEF (Ditlevsen and Daae, 2012) only took account of effective drilling and the dates of discharges. This meant that duration could be reduced considerably. The duration of each drilled section was estimated on the basis of a typical penetration rate for the top section of 10-25 metres per hour, with the topmost section accounting for the slowest speed. With such a scenario, the intervals for each section become three (for 36, 22 and 17½ inches) and four days (between 17½, 12¼ and 8½ inches).

The assumptions used in the modelling related to normal practice in drilling this type of well. WBM cuttings from the top 36- and 22-inch sections are discharged from the seabed in an upward direction, while discharges from the bottom sections will be brought up to the rig for treatment and released about one metre beneath the sea surface. Because the WBM cuttings are heavier than water, they will sediment to the seabed fairly quickly.

Treated OBM cuttings (from 17½, 12¼ and 8½ inches) are assumed in this modelling to be released one metre beneath the sea surface in a downwards direction. The discharges will sink in the water column, and an underwater cloud of small particles could form. Larger particles will sediment. At a certain point, the “cloud” will cease sinking and will disperse in the same way as water-soluble substances.

Modelling of the dispersion has been done for summer and winter conditions, with surface temperatures of 12°C and 7°C respectively. Table 7 presents the assumptions used in modelling the two conditions. The total amounts discharged are 940 tonnes of WBM cuttings from the two uppermost sections and 1 118 tonnes of PHD powder (treated OBM cuttings). In addition, 60 tonnes of bentonite and 299 tonnes of barite are released from the top sections and 386 tonnes of barite from the bottom sections. The quantity of treated OBM cuttings released in the modelling by Ditlevsen and Daae (2012) accords with the quantity used in Total’s discharge (Gabrielsen, 2005), which was 1 090 tonnes on the UKCS compared with 1 149 tonnes in Sintef’s modelling. This is accordingly regarded as a realistic discharge condition when OBM cuttings are involved and are thermal-treated in the rotormill. The results from Sintef’s modelling have therefore been used to determine exposure concentrations for particles in the water phase.

Dream modelling is based on the module developed for dispersion of cuttings (Rye et al, 1998, 2004 and 2008). The following results are presented by Ditlevsen and Daae (2012):

- Concentration and dispersion of particles in the water column
- Sedimentation on the seabed (both from the top sections and from discharges by the rig and by the rig alone)
- Cross-section and thickness of sedimentation on the seabed.

The results of the Dream modelling (Ditlevsen and Daae, 2012) of the particle concentration in the water column are summarised in
Figure 20 (summer condition) and Figure 21 (winter condition). The left-hand figure includes modelling the dispersion of both WBM (top sections released at the seabed) and treated OBM (the three bottom sections released from the rig) cuttings. The figures show cumulative maximum concentrations in the water column. With OBM cuttings released from the rig (right-hand figure), a maximum concentration of one-five ppm is demonstrated in the water column over an area of 400 x 3 500 metres and at depth of about 20 metres.

Table 7. Assumptions for cuttings quantity and composition in SINTEF's modelling (Ditlevsen and Daae, 2012).

Drilling section		36" drilling[1]	26" drilling[1]	17.5" drilling[2]	12.25" drilling[2]	8.5" drilling[2]
Start of discharge (month)		January/June	January/June	January/June	January/June	January/June
Section length (m)		88	370	1548	858	1390
Drilling (penetration) rate (m/h)		8	15	15	24	23
Discharge depth (m)		Seabed	Seabed	Surface	Surface	Surface
Diameter of outlet opening (m)		30 cm	30 cm	30 cm	30 cm	30 cm
Orientation of outlet opening		Vertical	Vertical	Vertical	Vertical	Vertical
		Upwards	Upwards	Downwards	Downwards	Downwards
Components	**Compound in discharge**	**Amounts**	**Amounts**	**Amounts**	**Amounts**	**Amounts**
Particles	Cuttings (tonn)	187.2	752.5			
Particles	PHD Powder (tonn)			752.5	205	160
Particles	Bentonite	18.7[3]	41.1[3]	0	0	0
Particles	Barite	93.6[3]	205.4[3]	135.5*	129*	121.5*
Chemical 1	Dispersed oil[4]			5000 ppm	5000 ppm	5000 ppm
Chemical 2	Aromatics[4]			178 ppm	178 ppm	178 ppm
Chemical 3	PAH2 TWMA[4]			5 ppm	5 ppm	5 ppm
	Water + plonor			135.5	129	121.5
	Sum MUD	**224**	**493**	**271**	**258**	**243**

*) Mud in m^3/m section length and density given by the operator, assumed 50% of this is barite and 50% is water and plonor

[1] Water based drilling mud
[2] Oil based drilling mud
[3] Assumtion of amount (Barite 50% of cuttings, Bentonite 10% of cuttings
[4] Chemical attached to the PHD powder

Modelling of dispersion on the seabed is shown in the Figures with a maximum thickness in millimetres on the seabed and in kg/sq.m, and as the median grain size for summer and winter conditions. Ditlevsen and Daae (2012) have modelled discharges from the top sections and from the rig.

Only results for discharges from the rig (treated OBM cuttings) in summer condition are shown in Figure 22. The left-hand figure shows that the maximum thickness on the seabed is 0.3-1 mm over an area corresponding to 200 x 600 metres. The right-hand figure shows that the maximum thickness is 1.8 mm in an area corresponding to 50 x 50 metres. Corresponding data for a winter condition show two areas of 50 x 50 metres with a maximum thickness of 0.65 mm. Figure 23 shows that 1-10 kg/m^2 in total cuttings quantity is the largest amount sedimented, while the contribution from treated OBM cuttings is 0.3-1 kg/m^2 over an area corresponding to 200 x 600 metres. Based on an assumed quantity of 5 g/kg of appended oil, 0.2 g/kg dm aromatics and 5 mg/kg dm of PAH, as presented in table 7, Ditlevsen and Daae (2013) have calculated the following maximum concentrations in the sediment: Oil: 1-10 g/m^2; aromatics and PAH < one g/m^2; barite: 1-10 kg/m^2; bentonite: 0.1-1 kg/m^2

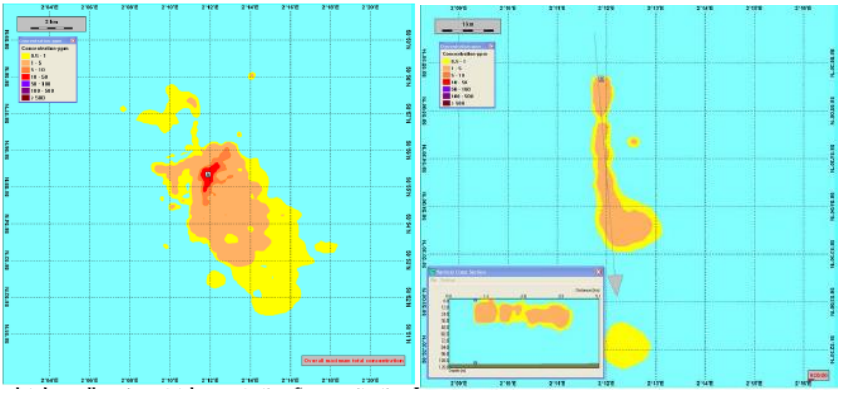


Figure 20. Modelling result for cumulative maximum concentrations of particles in the water column in summer condition when discharging from a well. Left: both WBM and OBM cuttings. Right: only OBM cuttings released from rig (Ditlevsen and Daae, 2012).

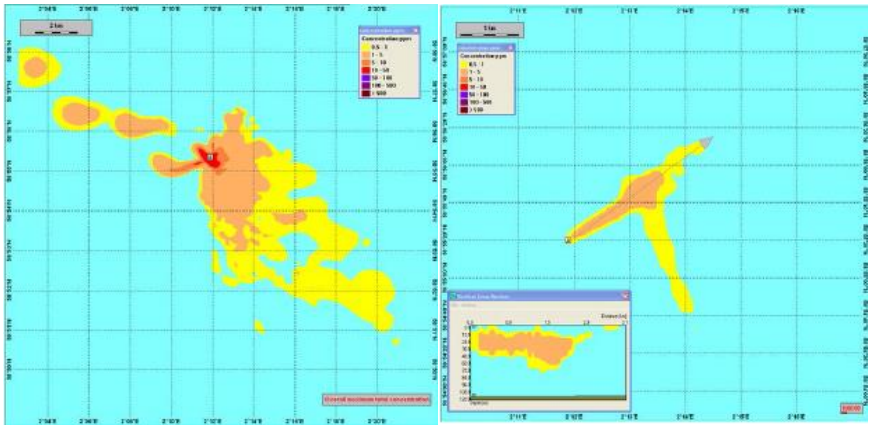


Figure 21. Modelling result for cumulative maximum concentrations of particles in the water column in winter condition when discharging from a well. Left: both WBM and OBM cuttings. Right: only OBM cuttings released from rig (Ditlevsen and Daae, 2012).

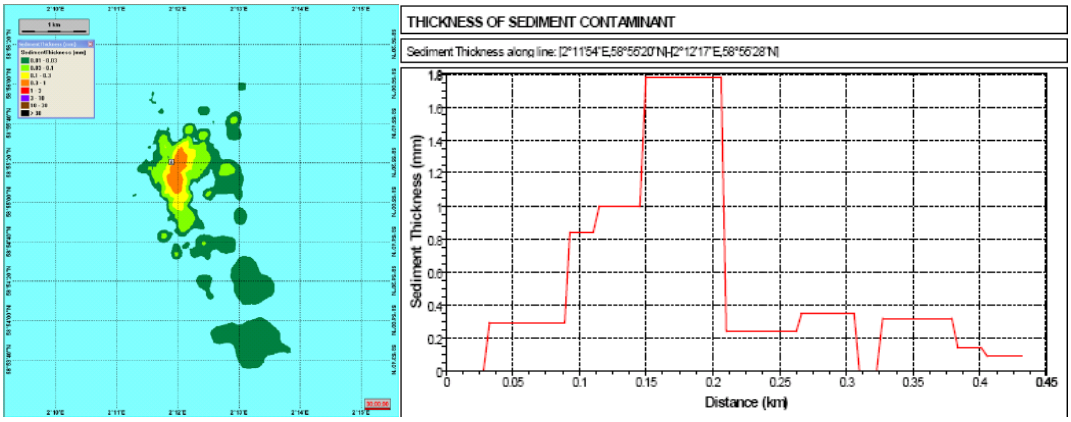


Figure 22. Dispersion of discharges from the rig on the seabed in summer condition. Left: millimetre thickness. Right: maximum thickness within 50 x 50 metres (Ditlevsen and Daae, 2012).

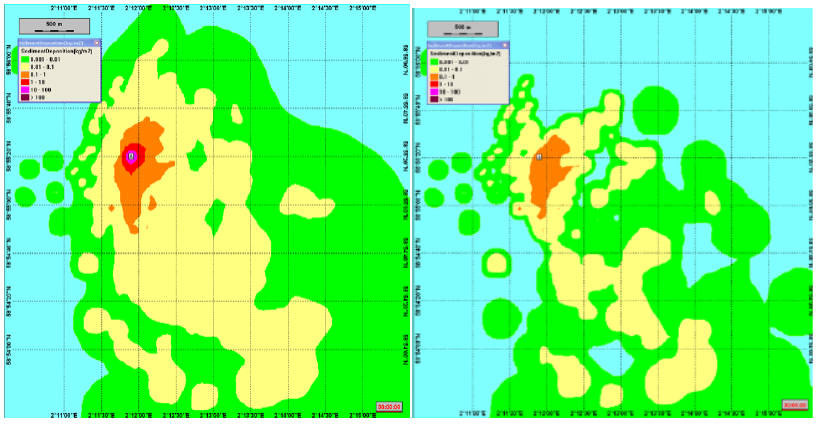


Figure 23. Material (kg) sedimented per sq.m of seabed. A thickness of one mm corresponds to one kg/sq.m. Left: all discharges (from seabed and rig). Right: contribution from treated cuttings.

5. Results and discussion

5.1. Oil content

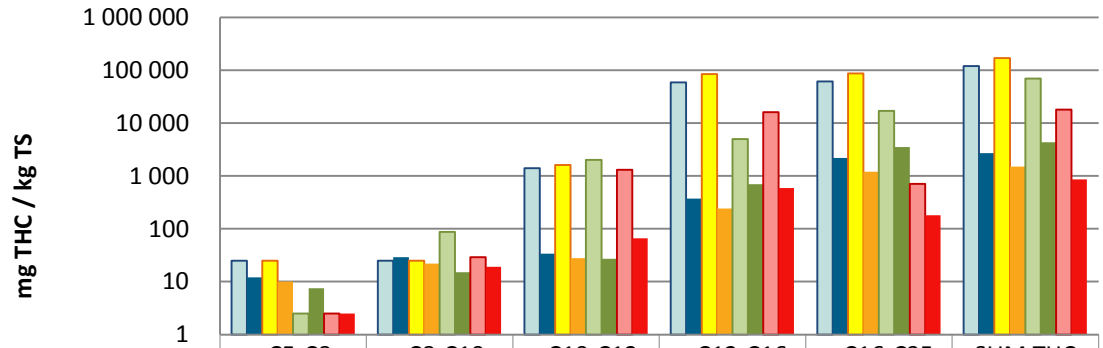
5.1.1. Drill cuttings

Analyses of the THC in the four sampling sets of treated cuttings show that all the samples after treatment contained < 10 g/kg dm oil (1 %). The content varied from 0.86 to 4.3 g/kg dm. See Table 8. Amundsen and Sørheim (2011) also analysed cuttings from Mongstad South, and this sample contained 2.9 g/kg dm oil– in other words, corresponding to the samples in this study. Compared with the analyses conducted in the study of TWMA's offshore facility (Graham, 2010), the oil content was somewhat higher. Graham's samples varied from 0.1 to 0.8 g/kg dm (0.01-0.08 %).

Table 8. Content of oil in treated cuttings in mg/kg dm.

Oil fractions	Oil concentration in treated cuttings (mg/kg dm)					
	Bioforsk study[1]		This study			
	No of samples	Result	Out 38	Out 41	Out 17	Out C
Fractions C_5-C_8	1	<7	10	12	8	<5
Fractions C_8-C_{10}	1	<10	22	29	15	19
Fractions C_{10}-C_{12}	1	<12	28	34	700	590
Fractions C_{12}-C_{16}	1	460	240	370	27	66
Fractions C_{16}-C_{35}	1	2 450	1 200	2 200	3 500	180
Total C_5-C_{35}		2 910	1 500	2 700	4 300	860

[1] Amundsen and Sørheim, 2011.



	>C5-C8	>C8-C10	>C10-C12	>C12-C16	>C16-C35	SUM THC
Leirstein inn (41)	25	25	1400	59000	61000	120000
Leirstein ut (41)	12	29	34	370	2200	2700
Kalkstein inn (38)	25	25	1600	84000	87000	170000
Kalkstein ut (38)	10	22	28	240	1200	1500
Leirstein inn (17)	3	87	2000	5000	17000	69000
Leirstein ut (17)	8	15	27	700	3500	4300
Cuxhaven inn	3	29	1300	16000	710	18000
Cuxhaven ut	3	19	66	590	180	860

Key: mg THC/kg TS = mg THC/kg dm; Leirstein inn/ut = In/Out Shale; Kalkstein inn/ut = In/Out Carbonate

Figure 24. Measured content of oil or THC (mg/kg dm) in the fractions (C_{5-8}, C_{8-10}, C_{10-12}, C_{12-16} and C_{16-35}) in untreated and treated cuttings.

Figure 24 presents the distribution of various hydrocarbon fractions (THC, oil) in the In and Out samples (mg/kg dm). The thermal treatment had little effect on the most water-soluble

hydrocarbon fractions (C_{5-8} and C_{8-10}). Removal primarily involves the heavier fractions. All four samples had a lower oil content than those used by SiINTEF in its dispersion modelling of TWMA-treated cuttings offshore. This utilised five grams of oil per kg dm.

These four samples show a cleaning effect of thermal treatment for OBM cuttings of 94-99 per cent. The oil content (sum of C_5 to C_{35}) was 2.7 g/kg dm and 1.5 g/kg dm in treated cuttings samples 41 and 38 respectively. The amount of fine powder (percentage by weight) smaller than two µm of total fine powder (< 2 mm) was about 20 per cent. Samples 17 and C had a significantly lower proportion of fine powder – six and nine per cent respectively of the fine powder (< 2 mm) was < two µm – and the oil content after treatment was 4.3 and 0.9 g/kg dm respectively.

Table 9. Content of oil in In and Out samples, treatment efficiency and fraction (volume %) of solids < 2 µm after treatment.

Sample ID	Oil (g/kg dm)	Sample ID	Oil (g/kg dm)	Treatment efficiency (%)	Fraction (vol % < 2 µm)
In 38	120	Out 38	1.5	99.1	20
In 41	170	Out 41	2.7	97.8	19.2
In 17	24	Out 17	4.3	93.8	5.9
In C	18	Out C	0.9	95.2	9.3

5.1.2. Leachate

Table 10 presents the content of oil in leachate (µg/l) from treated cuttings. When treated cuttings are discharged to the sea, the oil is likely to dissolve into the water phase. Leachate in the Bioforsk study (Amundsen and Sørheim, 2011), which involved 22 samples from Mongstad South, had results comparable with the findings here.

Table 10. Amount of oil leaching out from treated cuttings (µg/l).

Oil fraction	Oil concentration in Bioforsk study[1]		Oil concentration in our samples			
	No of samples	Result	Out 38	Out 41	Out 17	Out C
C_5-C_8	-	-	36	23	14	<5
C_8-C_{10}	-		140	140	31	19
C_{10}-C_{12}	1	84	120	110	8.4	8.4
C_{12}-C_{16}	1	129	79	78	15	14
C_{16}-C_{35}	1	289	48	32	<20	<20
	1	24		-		
Total C_5-C_{35}		426	423	383	78[2]	54[2]

[1] Amundsen and Sørheim, 2011
[2] Half the detection limit is used when the concentrations are lower than the reporting limit.

5.2. PAH

5.2.1. Cuttings

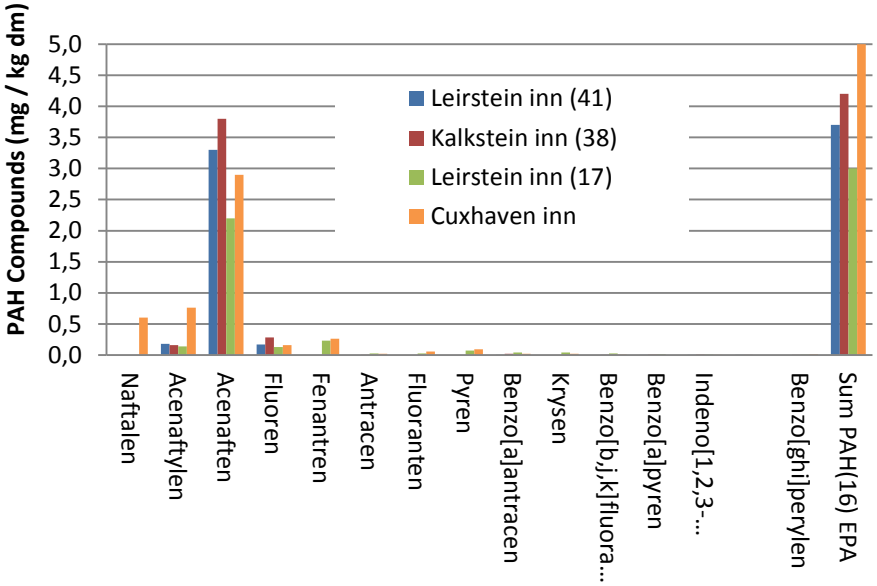
Concentrations of PAH were low in untreated cuttings samples, but 11 different PAH compounds were nevertheless identified. See table 11 and figure 25. Acenaphthene was the largest compound in the untreated samples. The total of PAH_{16} in samples In 38 and In 41 was reduced by 99 per cent through treatment. The treated samples satisfy condition class 2 – in other words, green (good) – for all components. Treatment did not give equally good results for the other two samples. Only a third of the PAH was removed in sample In 17, and four of the compounds in this sample were in condition class 3 – in other words, yellow (moderate). The condition class will be yellow for three compounds in the treated sample from Cuxhaven (Out C), and more stringent for benzo[ghi]perylene.

The classification system for coastal waters has been used, since a similar system does not exist for offshore waters. The total quantity of PAH on treated cuttings varied from 0.023 to one mg/kg dm. SINTEF used 5 mg/kg dm in its modelling.

Table 11. Concentration of PAH in mg/kg dm on untreated and treated cuttings. Samples from treated cuttings (Out) are labelled with the colour code from Weideborg et al (2012): blue = background, green = good, yellow = moderate, orange = poor and red = very poor.

Sample ID	Naphthalene	Acenaphthylene	Acenaphthene	Fluorine	Phenanthrene	Anthracene	Fluoranthene	Pyrene
In 38	<0.0005	0.160	3.800	0.280	<0.0005	0.005	<0.0005	<0.0005
Out 38	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
In 41	<0.0005	0.180	3.300	0.170	<0.0005	<0.0005	<0.0005	<0.0005
Out 41	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
In 17	<0.05	0.14	2.2	0.13	0.23	0.023	0.027	0.073
Out 17	0.25	0.011	0.18	0.024	0.17	0.023	0.045	0.091
In C	0.6	0.76	2.90	0.16	0.26	0.017	0.056	0.093
Out C	0.029	0.0079	0.01	0.0073	0.016	0.0029	0.008	0.017

Sample ID	Benzo[a]anthracene	Chrysene	Benzo[b,j,k]fluoranthene	Benzo[a]pyrene	Indeno[1,2,3-cd]pyrene	Dibenzo[a,h]anthracene	Benzo[ghi]perylene	Total PAH_{16}
In 38	0.017	<0.0005	0.002	0.010	0.011	0.006	0.006	4.200
Out 38	0.006	<0.0005	0.004	0.002	0.004	0.003	0.004	0.023
In 41	0.003	<0.0005	<0.0005	0.004	0.003	0.004	<0.0005	3.700
Out 41	0.012	0.002	0.014	0.003	0.011	0.004	0.006	0.053
In 17	0.042	0.041	0.025	0.013	0.011	<0.005	0.0081	3
Out 17	0.035	0.057	0.045	0.029	0.02	0.0065	0.012	1
In C	0.019	0.022	<0.005	<0.005	0.07	0.01	0.01	5
Out C	0.022	0.021	0.03	0.02	0.07	0.02	0.10	0.39



Key:Leirstein inn = In Shale; Kalkstein inn = In Carbonate; Naphthalene, Acenaphthylene, Acenaphthene, Fluorine, Phenanthrene, Anthracene, Fluoranthene, Pyrene, Benzo[a]anthracene, Chrysene, Benzo[b,j,k] fluoranthene, Benzo[a]pyrene, Indeno[1,2,3-cd]pyrene, Benzo[ghi]perylene, Total PAH_{16} EPA

Figure 25. Concentration of PAH in mg/kg dm for different components of PAH_{16} in untreated OBM cuttings.

Information on PAH concentrations in cuttings can be found in other reports. Results in the Bioforsk report (Amundsen and Sørheim, 2011), where analyses are conducted with a random selection of 15 samples from Mongstad during 2011, show that treated cuttings have

a PAH_{16} concentration of 0.065-3.28 mg/kg dm, with an average of one mg/kg dm. Three of our four samples have lower concentrations than the average of these.

5.2.2. Leachate

The results of the leaching studies show lower concentrations of PAH. Only naphthalene and phenanthrene have concentrations above the reporting limit. These two are also the most water-soluble of the PAH compounds.

Table 12. PAH results from leaching studies with the Out samples (µg/l).

Analytical parameter	Out 38	Out 41	Out 17	Out C
PAH_{16}	**(µg/l)**	**(µg/l)**	**(µg/l)**	**(µg/l)**
Naphthalene	0.33	0.06	0.15	0.092
Acenaphthylene	<0.01	<0.01	<0.01	<0.01
Acenaphthene	<0.01	<0.01	<0.01	<0.01
Fluorine	<0.01	<0.01	<0.01	<0.01
Phenanthrene	0.014	0.014	0.016	<0.01
Anthracene	<0.01	<0.01	<0.01	<0.01
Fluoranthene	<0.01	<0.01	<0.01	<0.01
Pyrene	<0.01	<0.01	<0.01	<0.01
Benzo[a]anthracene	<0.01	<0.01	<0.01	<0.01
Chrysene/triphenylene	<0.01	<0.01	<0.01	<0.01
Benzo[b]fluoranthene	<0.01	<0.01	<0.01	<0.01
Benzo[k]fluoranthene	<0.01	<0.01	<0.01	<0.01
Benzo[a]pyrene	<0.01	<0.01	<0.01	<0.01
Indeno[1,2,3-cd]pyrene	<0.002	<0.002	<0.002	<0.002
Dibenzo [a,h]anthracene	<0.01	<0.01	<0.01	<0.01
Benzo[ghi]perylene Total	<0.002	<0.002	<0.002	<0.002
Total PAH_{16}	0.40[1]	0.13[1]	0.23[1]	0.16[1]

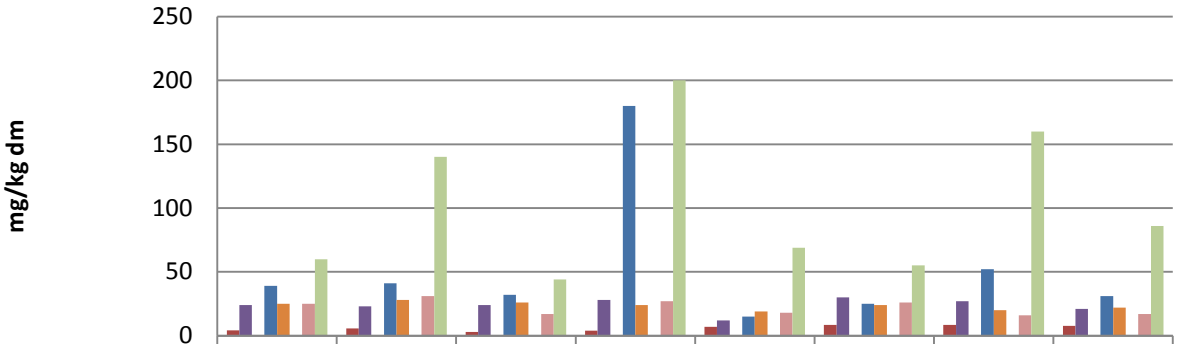
[1] Half the reporting limit is used when calculating the sum of PAH for compounds < LOQ.

5.3. Metals and barium

5.3.1. Drill cuttings

Figure 26 presents measured concentrations of heavy metals in untreated and treated cuttings. Figure 27 presents barium concentrations measured in the same samples. Treatment of cuttings was not expected to produce changes in the concentrations of heavy metals and barium. Nevertheless, two of the samples (41 and 38) showed an increased concentration of copper and zinc in the Out sample compared with the In sample. This could reflect the actual sampling process, where the sample was cooled in a metal bucket (zinc) before transfer to its final packaging. It could also be a result of the treatment process itself, with zinc and copper alloys from the mill itself contaminating the samples. When a stainless steel bucket was used in the next sampling round, sample 17, the zinc values were not increased.

Results in the Bioforsk report (Amundsen and Sørheim, 2011), where a random selection of samples from Mongstad were analysed, show concentrations for treated cuttings which correspond with our samples. The results are presented in the table below together with our Out samples. The concentrations are compared with the Norwegian Environment Agency's sediment classification (Weideborg et al, 2012), and show that the samples have concentrations in line with the background – or good – level for all parameters except copper in the Out 38 sample. Table 13 compares the Bioforsk results from 22 different samples from Mongstad South with the four samples studied in this report.

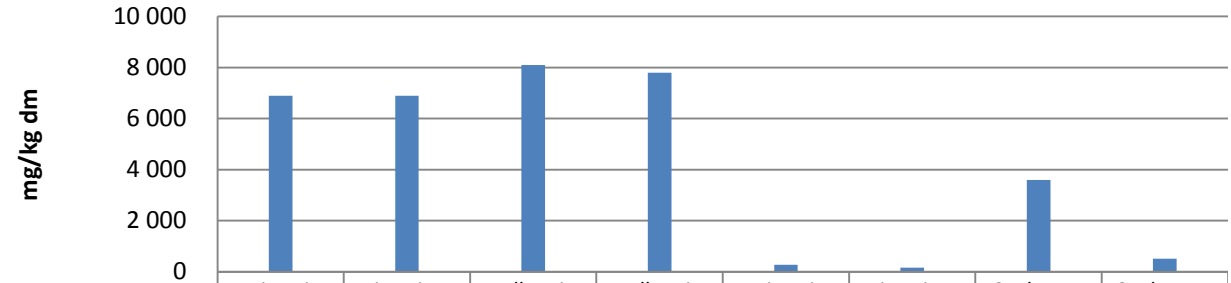


	Leirstein inn (41)	Leirstein ut (41)	Kalkstein inn (38)	Kalkstein ut (38)	Leirstein inn (17)	Leirstein ut (17)	Cuxhaven inn	Cuxhaven ut
Arsen (As)	4,3	5,6	2,9	4,0	6,9	8,4	8,5	7,8
Bly (Pb)	24	23	24	28	12	30	27	21
Kadmium (Cd)	0,36	0,22	0,06	0,08	0,18	0,13	0,22	0,13
Kobber (Cu)	39	41	32	180	15	25	52	31
Krom (Cr)	25	28	26	24	19	24	20	22
Kvikksølv (Hg)	0,035	0,087	0,017	0,07	0,043	0,025	0,073	0,008
Nikkel (Ni)	25	31	17	27	18	26	16	17
Sink (Zn)	60	140	44	200	69	55	160	86

Key: Leirstein inn/ut = In/Out Shale; Kalkstein inn/ut = In/Out Carbonate; Arsenic (As), Lead (Pb), Cadmium (Cd), Copper (Cu), Chromium (Cr), Mercury (Hg), Nickel (Ni), Zinc (Zn)

Figure 26. Concentrations of heavy metals (mg/kg dm) in untreated and treated OBM cuttings.

No classification levels exist for barium. Its level in the Out samples was very high compared with the samples in the Bioforsk report. Barium is a weighting material used during drilling, and cuttings are accordingly not comparable with normal sediment. Studies have demonstrated background barium levels of 131 mg/kg dm (median value) in non-polluted sediment, but varying between 4.6 and 554 mg/kg dm. Measured concentrations in Out samples 41 and 38 were significantly higher than this.



	Leirstein inn (41)	Leirstein ut (41)	Kalkstein inn (38)	Kalkstein ut (38)	Leirstein inn (17)	Leirstein ut (17)	Cuxhaven inn	Cuxhaven ut
Barium	6900	6900	8100	7800	270	160	3600	510

Key: Leirstein inn/ut = In/Out Shale; Kalkstein inn/ut = In/Out Carbonate

Figure 27. Concentration of Ba in mg/kg dm in untreated and treated OBM cuttings.

Table 13. Monthly results in Bioforsk report and our samples in mg/kg. Blue = background, green = good, yellow = moderate, orange = poor and red = very poor.

Metals	Heavy metal concentrations from Bioforsk report[1] (mg/kg dm)				Heavy metal concentrations measured in these samples (mg/kg dm)			
	No of samples	Min	Max	Average	Out 38	Out 41	Out 17	Out C
Arsenic	22	2.9	12	8	4.0	5.6	8.4	7.8
Lead	23	13	89	29	28	23	30	21
Cadmium	23	0.2	3	1	0.1	0.2	0.13	0.13
Copper	23	39	73	54	180	41	25	31
Chromium	22	25	81	35	24	28	24	22
Mercury	23	0.0	0.21	0.1	0.1	0.1	0.025	0.008
Nickel	23	18	48	33	27	31	26	17
Zinc	23	53	470	115	200	140	55	86
Barium	22	700	17 000	5 980	7 800	6 900	160	510

[1] Amundsen og Sørheim, 2011.

5.3.1. Leachate

Table 14 presents the results of leaching studies conducted with the four samples of treated OBM cuttings. The results are compared with those obtained by Amundsen og Sørheim (2011) from their study. The results of these two studies correspond fairly well.

Table 14. Results from leaching studies by Bioforsk and with our samples in mg/kg, converted from tests carried out with a 1:10 ratio between solids and liquids.

Metals	Heavy metal concentrations from Bioforsk report[1] (mg/kg dm)				Heavy metal concentrations measured in these samples (mg/kg dm)			
	No of samples	Min	Max	Average	Out 38	Out 41	Out 17	Out C
Arsenic	4	0.026	0.080	0.051	0.026	0.023	<0.01	0.16
Lead	5	0.00216	0.0216	0.0092	0.0071	0.0031	0.0026	<0.002
Cadmium	2	<0.0005	<0.0005	<0.0005	<0.002	<0.002	<0.002	<0.002
Copper	5	0.357	0.863	0.591	0.59	0.46	0.26	0.17
Chromium	5	0.0414	0.137	0.1039	0.09	0.1	0.03	0.024
Mercury	2	<0.0002	0.0002	0.0002	<0.0005	<0.0005	<0.0005	0.0008
Nickel	5	0.413	1.11	0.7672	0.46	0.4	0.45	0.46
Zinc	5	<0.02	0.0557	0.0289	0.032	0.031	0.061	0.1
Barium	2	1.62	6.04	3.83	1.1	0.94	1.4	1.4

[1] Amundsen og Sørheim, 2011

5.4. Particle and dry matter analyses

5.4.1. Dry matter and volatile dry matter

Total dry matter (dm) and volatile dry matter (vdm) in the samples are summarised in Table 15. The oil content in the cuttings is also summarised as percentage oil on a dry matter basis. The liquid content in the cuttings samples has been reduced through thermal treatment from 20-44 % to < 1 %. TTC thermal treatment has substantially reduced the organic content in all the cuttings samples because a large volume of oil has been removed from them. Based on measured oil concentrations, In samples 41 and 38 from Mongstad had the highest oil content. The other In samples had much lower oil content. The oil removal in Mongstad was much higher than in Cuxhaven; between 95.2-99.1 % oil removal compared to 39 % on the latter.

Table 15. Dry matter (dm) and volatile dry matter (vdm) in untreated and treated OBM cuttings.

Sample ID		DM g/kg	VDM g/kg	% VDM of DM	Solids (%)	Liquid (%)	Oil[1] (%)
In	38	713	60.9	8.5	71.3	28.7	12
Out		993	40.5	4.1	99.3	0.7	0.27
In	41	798	70.0	8.8	79.8	20.2	17
Out		990	42.2	4.3	99.0	1.0	0.15
In	C	795	90.2	11.4	79.5	20.5	0.69
Out		997	91.9	9.2	99.7	0.3	0.42
In	17	561	51.8	9.2	56.1	43.9	1.8
Out		990	64.3	6.5	99.0	1.0	0.086

[1] Calculated from measured oil content (g/kg dm).

5.4.2. Particle size distribution (PSD)

Sediments and soil are characterised by the PSD of the fine fractions (< 2 mm). The particles are split into three fractions: clay (< 2 µm), silt (2-60 µm) and sand (>60 µm). See Figure 28. Soil type triangle which specifies the designations of soil/sediments on the basis of their relative content on particle sizes; sand, silt and clay. The results from the PSD (weight-based) using the pipette method are presented in Table 16 and in Figure 28 and Figure 29.

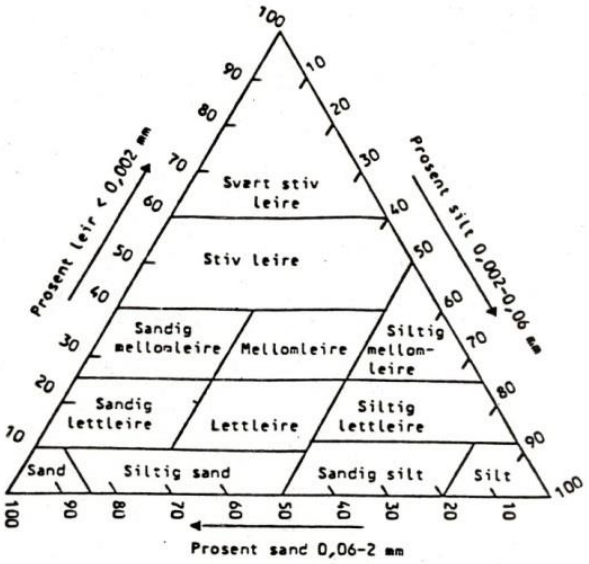
Samples 38 and 41 have the largest proportion of clay. Little difference in PSD exists between treated cuttings in samples Out 41 and Out 38. All grain sizes are present in these samples, and they are evenly distributed. No fractions stand out particularly. With the samples taken directly from the mill, 65 and 55 weight % passed the 2 mm (coarse sand) sieve for samples Out 38 and Out 41 respectively. Approximately 20 % of both samples were < 2 µm (clay). This grain size distribution is to be regarded as stiff and very stiff clay.

Sample Out 17 was more finely ground, and almost 87 weight % passed the 2 mm sieve, but it had more uneven and coarser grinding, only 8 % < 2 µm. Based on grain size distribution it is considered silty light clay.

The Out C sample from Cuxhaven also had a fairly uneven PSD. It was more finely crushed than the Out 38 and 41 samples. 78 % of the sample passed the 2 mm sieve. The clay content was higher than in the Out 17 sample, but lower than samples Out 38 and Out 41 – in other words, about 23 % < 2 µm.

Table 16. Composition of treated cuttings (percentage of particles < two mm).

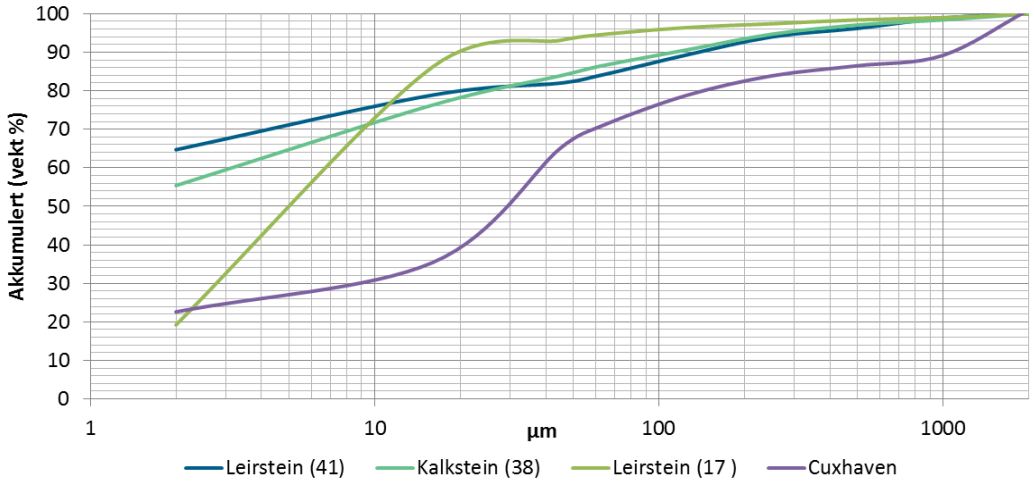
Sample ID	Sand %	Silt %	Clay %	Soil type name
Out 41	15.9	19.4	64.7	Very stiff clay
Out 38	13.5	31.1	55.4	Stiff clay
Out 17	5.4	75.4	19.2	Silty light clay
Out C	29.1	48.3	22.6	Light clay



Key: Prosent leire = % clay (< 2 µm); Prosent silt = % silt (<60 µm and > 2µm) ; Prosent sand = % sand (< 2 mm and > 60 µm).

Figure 28. Soil type triangle which specifies the designations of soil/sediments on the basis of their relative content on particle sizes; sand, silt and clay.

When discharged, clay particles will very probably remain in suspension in the water column for a relatively long time before they sediment. However, they could flocculate, lumping them together in salt water and become naturally larger. That would increase the sedimentation speed significantly (van Olphen, 1963).



Key: Akkumulert= accumulated (weight %); Leirstein 0 Shale; Kalkstein = Carbonate

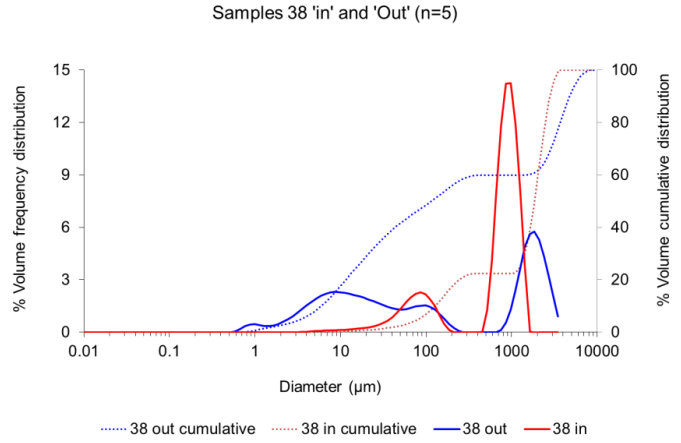
Figure 29. PSD (weight %) of treated OBM cuttings for particles from 2 µm-2mm.

Results from the Malvern Mastersizer measurements of the untreated and treated cuttings samples are summarised in Table 17. Figure 30 presents the PSD for all In and Out samples from the four sample series. The Out samples contain a larger proportion of small particles than the In ones. The hammermill reduces particle size. D_{50} (50 volume % undercut diameter) for all Out samples varies from 7 to 77 µm. The sizes and types of solid matter in the In samples going to the hammermill are crucial for the size of particles in the Out samples.

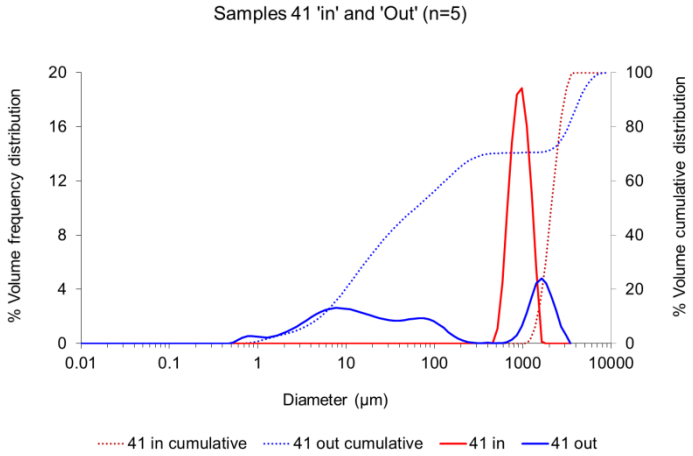
Table 17. PSD determined by the Malvern Mastersizer. Analyses of untreated and TCC-treated samples. Particle diameters are in µm.

Diameter	In 38	Out 38	In 41	Out 41	In 17	Out 17	In C	Out C
d_{10}[1] (µm)	72	4.2	706	3.6	3.5	0.97	36	25.5
d_{50}[2] (µm)	876	66.2	987	36.3	21.7	7.72	130	76.7
d_{90}[3] (µm)	1 300	2 130	1 360	1 970	290	97	213	157

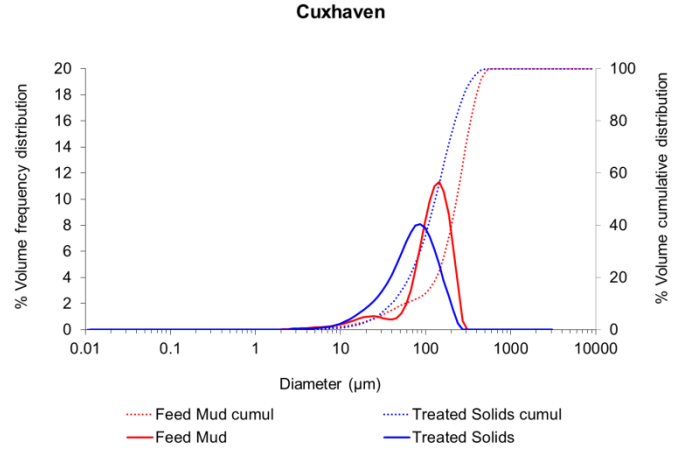
[1] d_{10}[1] : diameter which 10 vol % of the particles are smaller than. [2] d_{50}: diameter which 50 vol % of the particles are smaller than. [3] $d_{50:}$ diameter which 90 vol % the particles are smaller than.



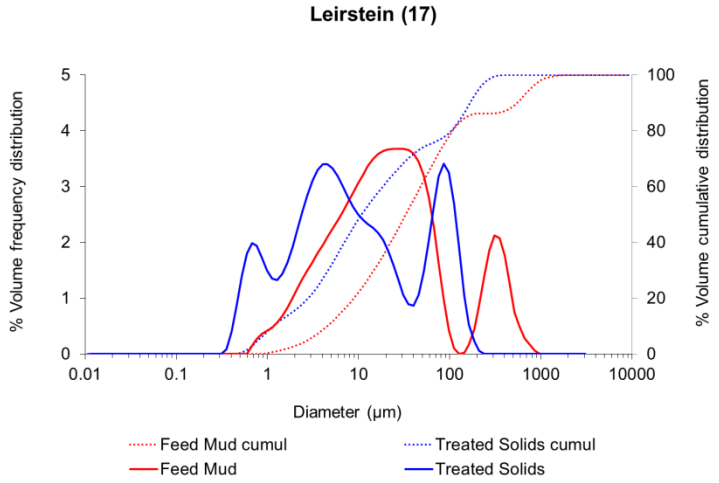
a)



b)



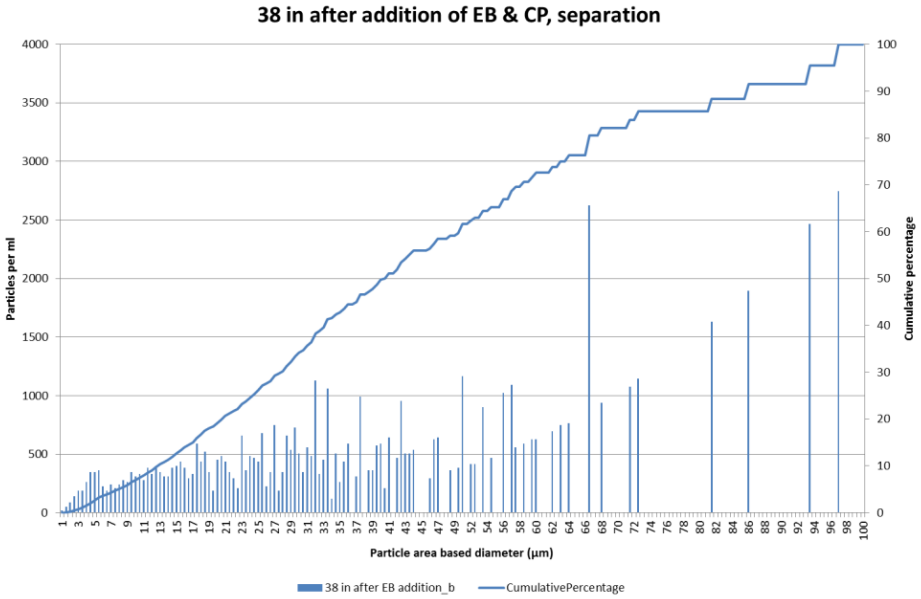
c)

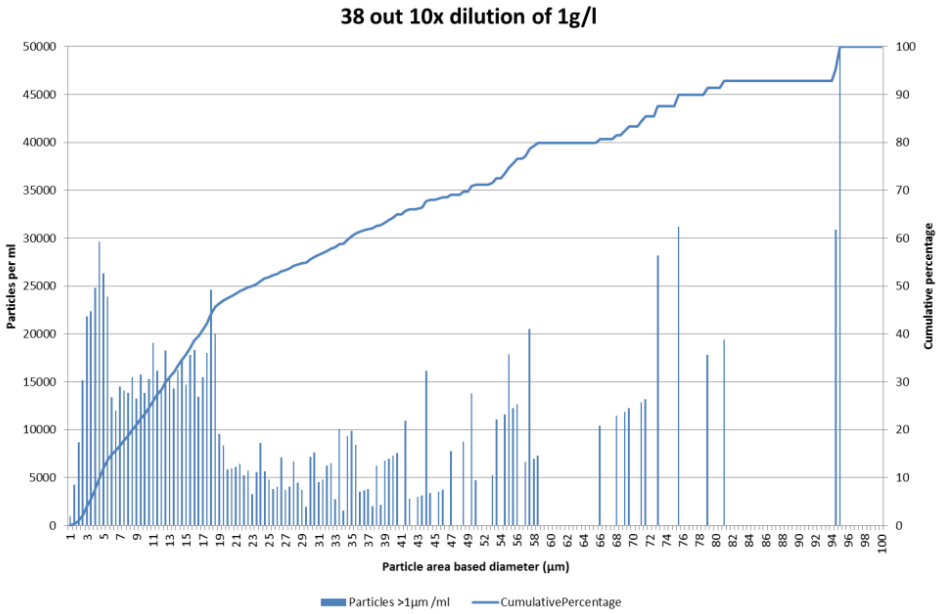


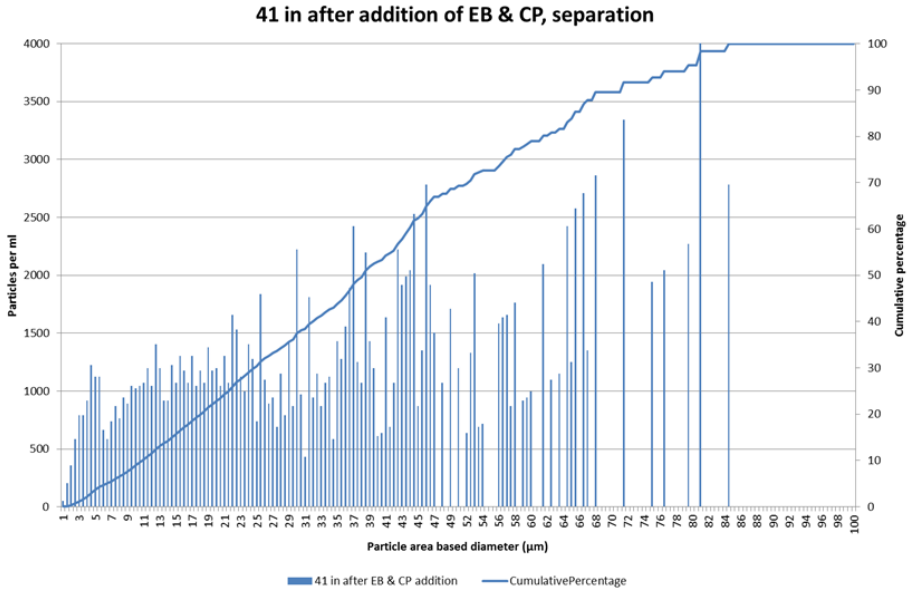
d)

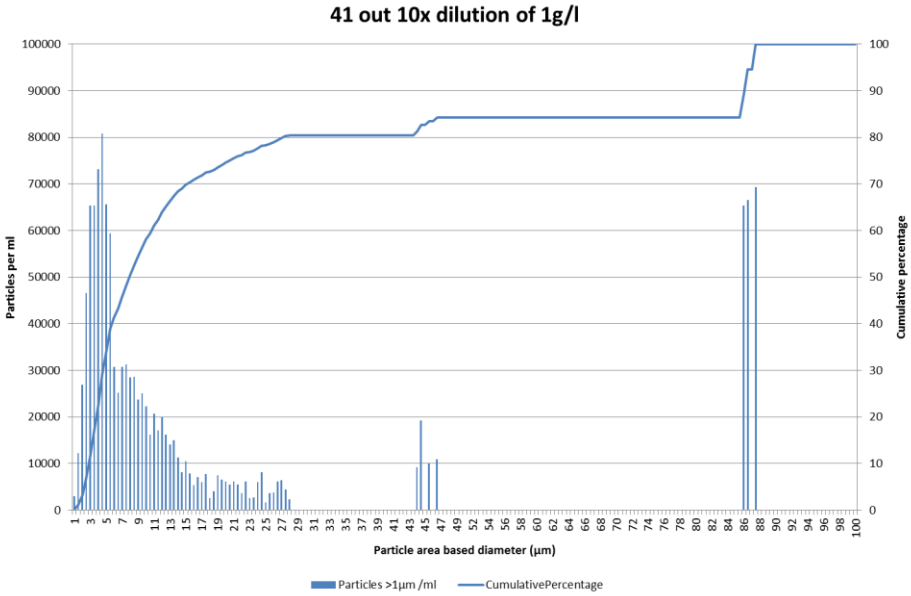
Figure 30. PSD of untreated and treated cuttings samples: (a) In and Out 38, (b) In and Out 41, (c) In and Out Cuxhaven and (d) In and Out 17.

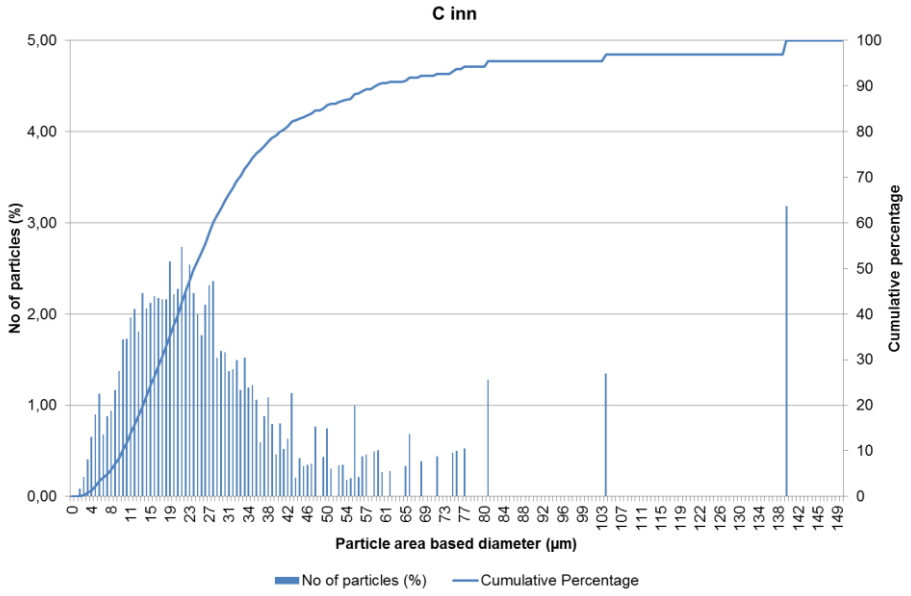
The characteristics of the smallest particles in each sample were investigated in more detail with FlowCam. The PSD is presented in Figure 31, and detailed particle properties are summarised in Table 18. The figure illustrates how the hammermill process reduces particle size. Although the reduction in the mean particle diameter was only 30-40 per cent, the PSD diagram shows a significant displacement of particle size towards the smaller area. The FlowCam results specify the number of particles per ml and the cumulative distribution is in relation to the number of particles between one and 100 µm. Comparing In 38 and Out 38 shows that d_{50}, or 50 % of the number of particles per ml, is < 40 µm in the In sample and < 20 µm in the Out sample. Corresponding data for sample 41 show an even larger change in PSD. D_{50} changes from 37 µm to 7 µm through treatment of the samples in the hammermill. Sample C (Cuxhaven) shows almost no change in d_{50}, which is about 27 µm for both. The same is the case for sample 17, where d_50 is 16 µm for both In and Out samples. The biggest proportion of large particles – sand and silt – is found in these two samples.

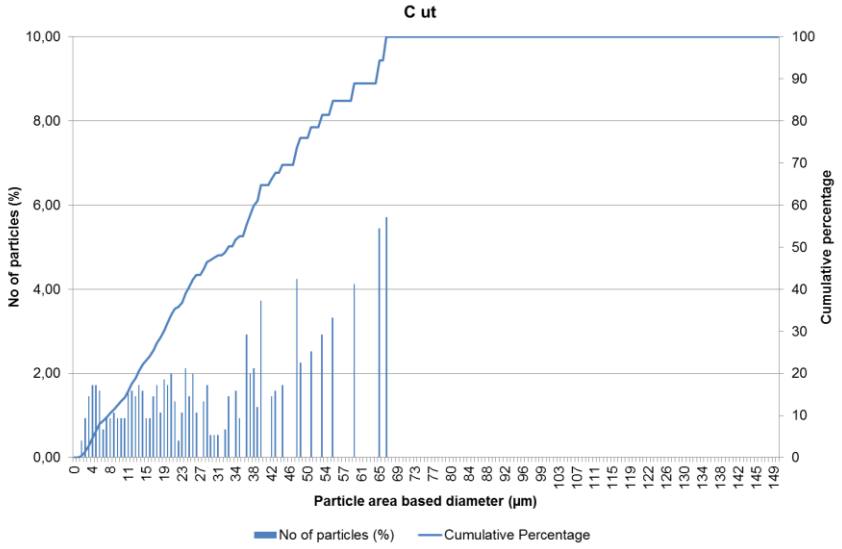


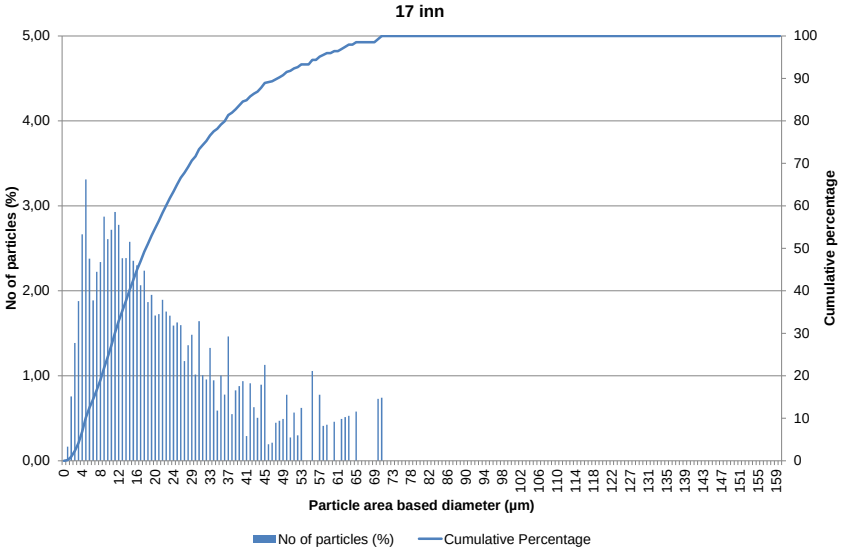

38 out 10x dilution of 1g/l
Particles per ml
Cumulative percentage
Particle area based diameter (µm)
Particles >1µm /ml
CumulativePercentage

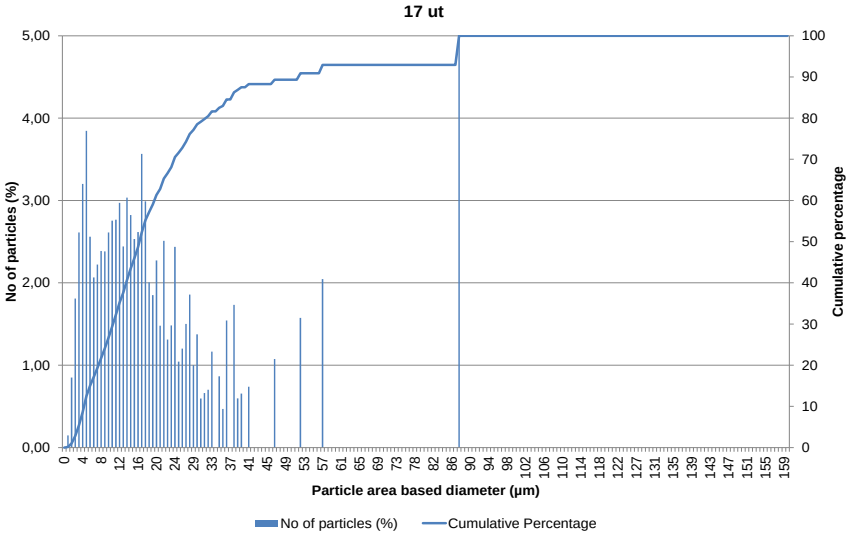

41 in after addition of EB & CP, separation
Particles per ml
Cumulative percentage
Particle area based diameter (µm)
41 in after EB & CP addition
CumulativePercentage


41 out 10x dilution of 1g/l
Particles per ml
Cumulative percentage
Particle area based diameter (µm)
Particles >1µm /ml
CumulativePercentage


C inn
No of particles (%)
Cumulative percentage
Particle area based diameter (µm)
No of particles (%)
Cumulative Percentage


C ut
No of particles (%)
Cumulative percentage
Particle area based diameter (µm)
No of particles (%)
Cumulative Percentage


17 inn
No of particles (%)
Cumulative percentage
Particle area based diameter (µm)
No of particles (%)
Cumulative Percentage



Key: Inn = In; Ut = Out

Figure 31. PSD of cuttings samples determined by FlowCam. The left-hand y axis presents the number of particles per ml, while the right-hand y axis presents the cumulative distribution between one and 100 µm.

Figure 32 and
Figure 33 present microscopic images from FlowCam. The images in Figure 32 show that particles in samples 38 and 41 have been ground down to smaller sizes and have gained an even more rounded form. Relatively few particles have sharp or pointed edges.

Figure 33 presents In and Out particles from samples 17 and C (Cuxhaven). Sample C shows little change in particle size, but more rounding of the particles as a result of the treatment in the hammermill. Where sample 17 is concerned, particle size appears to have experienced little reduction but the particles are somewhat more rounded.

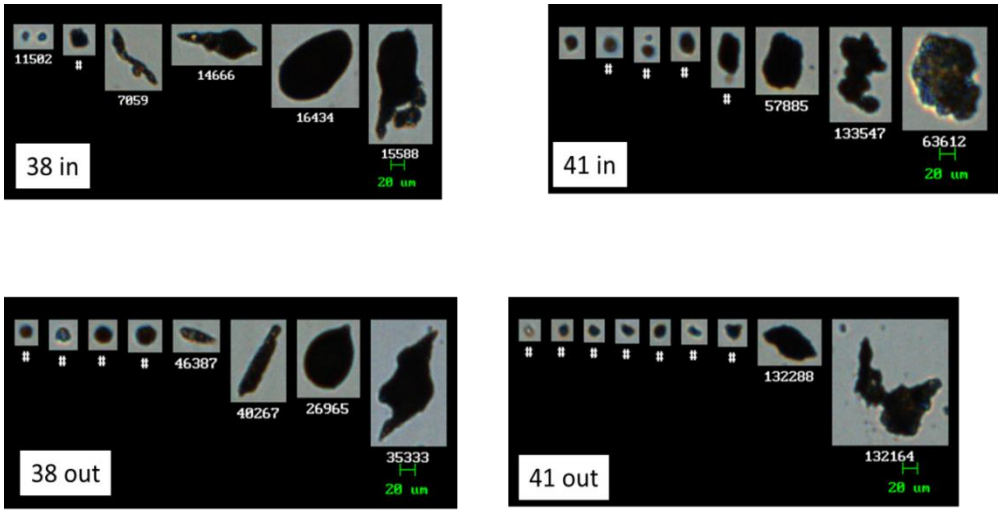
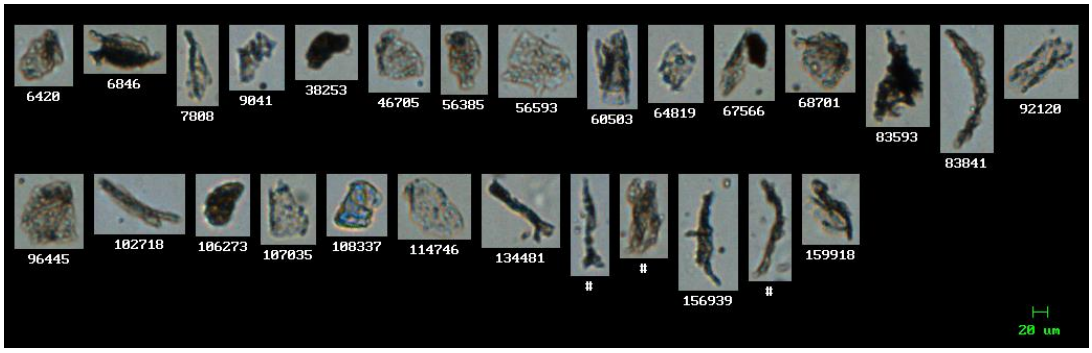
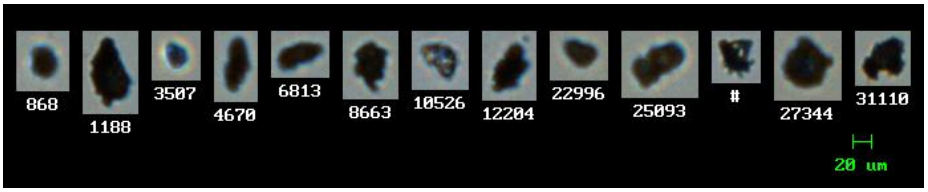


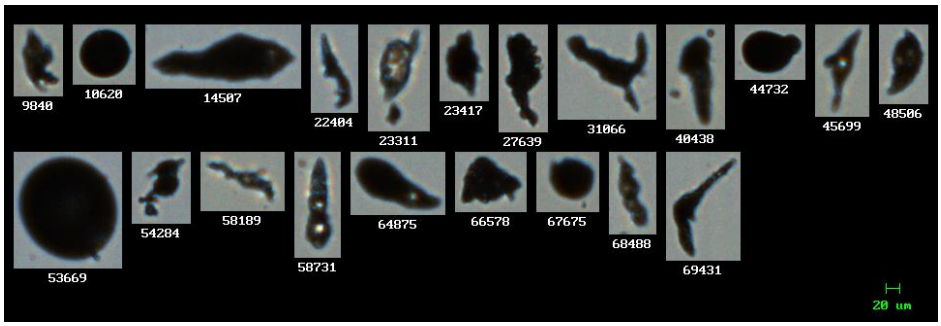
Figure 32. Images from shale (41) and carbonate (38) cuttings samples show a rounded form for the particles.



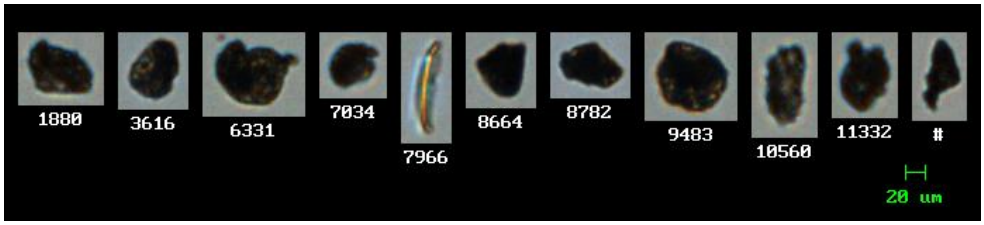
In 17



Out 17



In C



Out C

Figure 33. Images of shale (17) and Cuxhaven (C) cuttings samples show a rounded form for both sets of particles. The particles in the C samples were larger than those in sample 17.

5.4.3. Morphology

Particle analysis conducted with FlowCam has been used to determine the morphology of the particles. Treatment with the TCC process reduces particle size. Even if the reduction in the mean particle size was only 30-40 per cent, the distribution in the diagrams (Figure 30 and Figure 31) shows a significant displacement of particle size toward the smaller end for samples 38 and 41. The treatment has caused insignificant changes to the form of the particles, as indicated by the similarity of the values for various parameters, including aspect ratio and circular form, between untreated and treated samples. The values for roughness are by and large close to one, which indicates that most of the particles are non-porous. The close relationship between the ABD and ESD values indicates that most of the particles are regular in shape and can be compared with spheres, even though irregularities occur. See the digital images of individual particles in Figure 32 and Figure 33.

Table 18. Morphology for the cuttings samples. Comparison of In and Out samples 38, 41 and 17 from Mongstad South and sample C from Cuxhaven.

Sample	In 38		Out 38		In 41		Out 41	
	Average	Std dev	Average	Std dev	Average	Std dev	Average	Std dev
Height/breadth ratio	0.7	0.12	0.71	0.13	0.68	0.14	0.71	0.13
Circular conformity	0.87	0.08	0.88	0.07	0.86	0.09	0.88	0.07
Diameter (ABD, µm)	4.79	5.09	3.46	2.73	3.86	4.27	3.12	1.79
Diameter (ESD, µm)	6.17	7.79	3.99	3.45	4.8	5.6	3.58	2.34
Edge gradient	60	35.14	57.47	28.83	58.22	35.17	61.61	32.33
Length	7.7	10.64	4.69	4.27	5.78	6.93	4.2	2.99
Circumference	30.07	36.99	19.41	16.46	23.3	25.64	17.54	12.43
Roughness	1.11	0.07	1.09	0.03	1.1	0.06	1.09	0.03
Transparency	0.15	0.1	0.11	0.07	0.14	0.11	0.11	0.07
Volume (ESD)	1492.9	6925.68	241.12	5054.99	743.38	7877.84	111.17	8091.61
Breadth	4.3	4.28	3.18	2.59	3.62	4.02	2.85	1.72

Sample	In 17		Out 17		In C		Out C	
	Average	Std dev	Average	Std dev	Average	Std dev	Average	Std dev
Height/breadth ratio	0.69	0.13	0.71	0.12	0.69	0.14	0.72	0.12
Circular conformity	0.86	0.08	0.87	0.07	0.84	0.1	0.88	0.06
Diameter (ABD, µm)	3.7	3.16	3.72	2.96	5.71	5.41	3.56	3.41
Diameter (ESD, µm)	4.4	4.13	4.29	3.57	6.91	6.8	4.04	3.99
Edge gradient	63.02	31.4	63.76	34.3	59.73	33.04	65.33	33.5
Length	5.26	5.21	5.04	4.28	8.25	8.25	4.7	4.74
Circumference	21.44	19.6	20.98	16.9	33.17	29.6	19.41	17.92
Roughness	1.1	0.03	1.09	0.03	1.1	0.04	1.09	0.03
Transparency	0.12	0.08	0.11	0.07	0.14	0.09	0.1	0.06
Volume (ESD)	329.22	4293.23	223.75	2836.87	1181.58	12007.14	334.17	4220.12
Breadth	3.4	2.93	3.45	2.86	5.36	5.15	3.3	3.21

5.4.4. Sedimentation studies

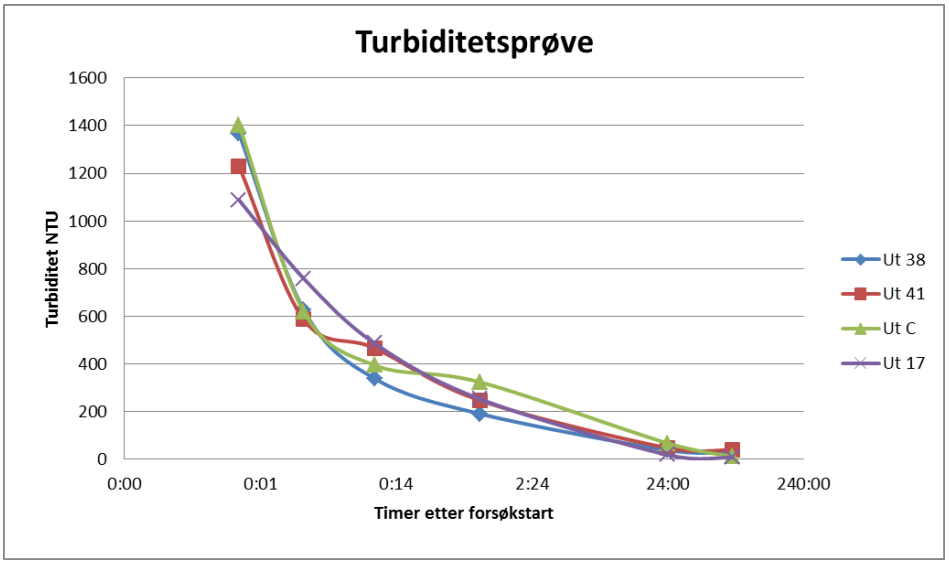
The sedimentation studies demonstrate that sedimentation occurs rapidly. This is clearly illustrated by the images shown in Figure 19. Turbidity in all the samples is reduced from > 1 000 nephelometric turbidity units (NTU) to < 800 NTU in the space of three minutes. See Figure 34.

The particle content after 72 hours of sedimentation is presented in Table 19. The content of suspended solids has then been reduced to 7.3-28.6 mg/l, depending on sample type. Compared with the samples added to the water column at the start of sedimentation, the organic material fraction on the samples released has increased after 72 hours of sedimentation. This emphasises that the particles which remain in the water column after 72 hours have a bigger proportion of adhering oil. These will be small particles with a large surface area.

The PSD is determined with a Malvern Mastersizer for all samples. See the comparisons in Figure 35. All individual analyses are presented in the appendix. Samples have been taken after 24 hours and analysed with FlowCam. The PSD is presented in
Figure 37 and the microscope images in Figure 36. Table 20 presents the morphology of the samples taken after 24 hours. The Malvern figures illustrate that a flocculation of particles occurs in some of the samples, which then gives increased sedimentation after a time. This is illustrated for samples 17 and C. Sample 17 has an average particle diameter at d_{50} of 3 µm after 60 minutes, increasing to 5 µm after 24 hours and then decreasing again to 1.5 µm after 72 hours. This process is described by van Olphen (1964).

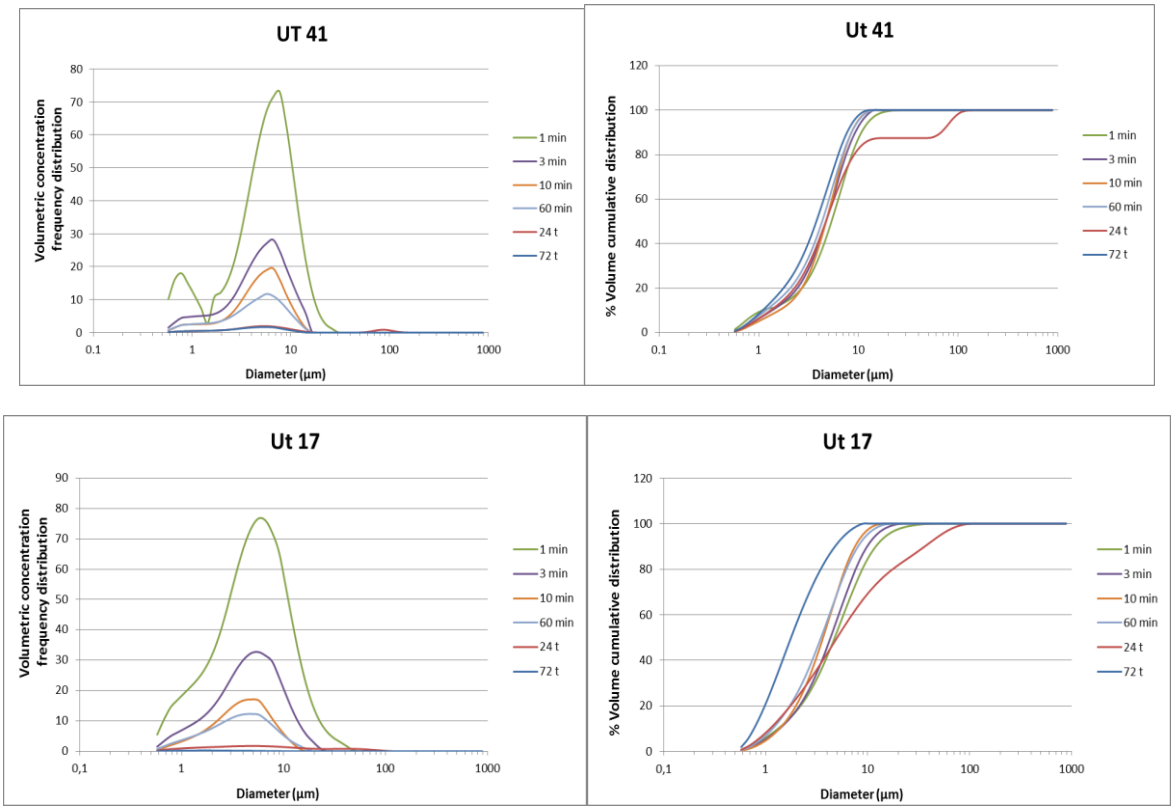
Table 19. Particle content after 72 hours of sedimentation.

Sample	Turbidity (NTU)	TSS (mg/l)	VDM (mg/l)	VDM/TSS (%)	VDM/DM original cuttings (%)
Out 38	28	28.6	5.2	18	4.1
Out 41	40	9.8	3.6	37	4.3
Out 17	8	7.3	2.1	29	9.2
Out C	12	25.6	4.7	18	6.5



Key: Turbiditetsprøve = Turbidity sample; Turbiditet NTU = Turbidity NTU; Timer etter forsøkstart = Hours after test start

Figure 34. Turbidity changes over time after test start. Samples are taken after one minute, three minutes and 72 hours.



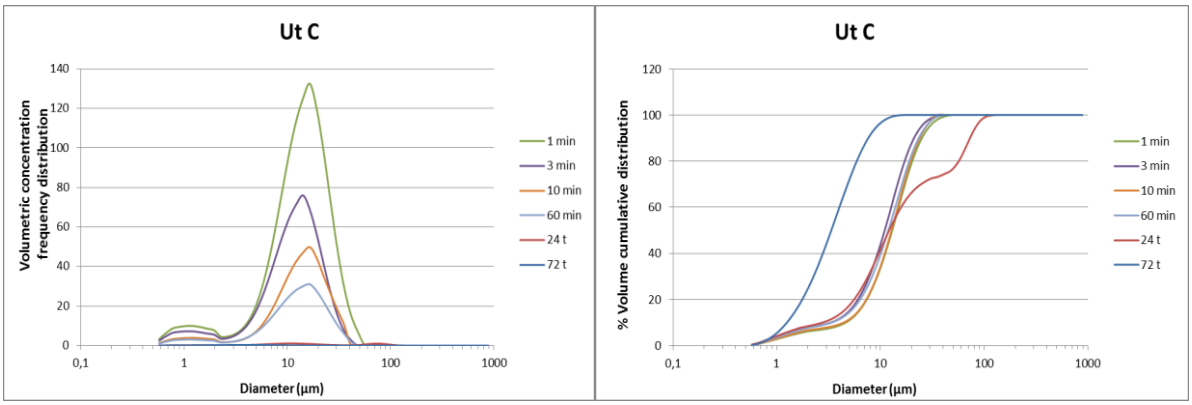
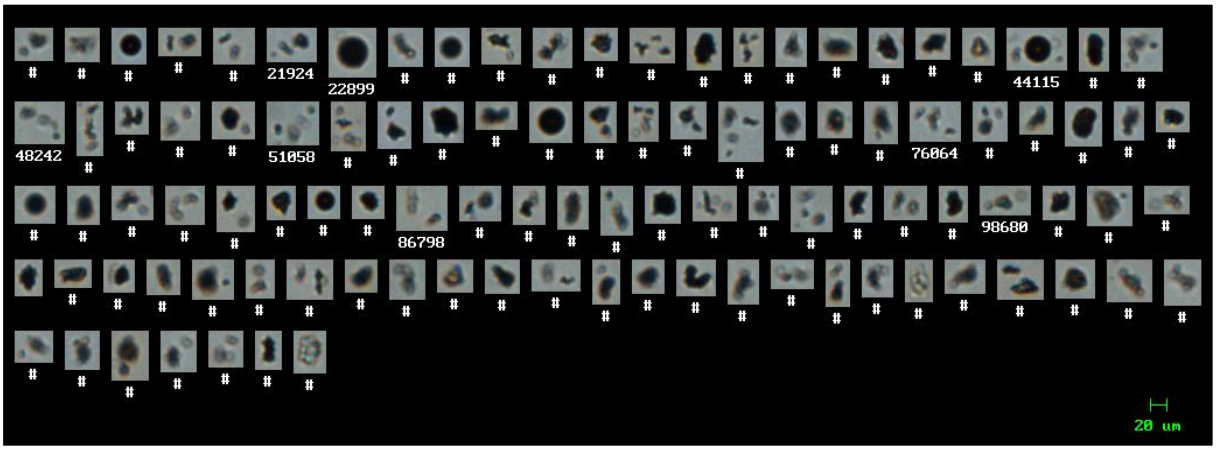


Figure 35. PSD determined by a Malvern Mastersizer in samples taken after one, three, 10 and 60 minutes and after 24 and 72 hours.

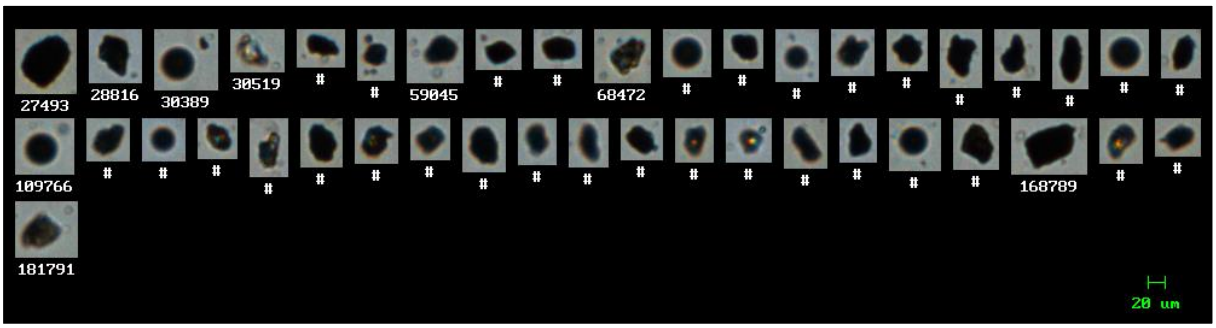
Table 20. Analysis results from FlowCam related to the morphological properties of particles in samples after 24 hours of sedimentation.

Sample	Out 38		Out 41		Out 17		Out C	
	Average	Std dev	Average	Std dev	Average	Std dev	Average	Std dev
Height/breadth ratio	0.69	0.69	0.69	0.13	0.69	0.14	0.65	0.15
Circular conformity	0.85	0.85	0.85	0.08	0.87	0.08	0.83	0.09
Diameter (ABD, µm)	5.22	5.22	4.47	2.39	3.25	2	5.65	5.3
Diameter (ESD, µm)	6.17	6.17	5.25	3.2	3.85	2.77	6.76	6.32
Edge gradient	79.81	79.81	72.52	38.31	59.93	32.93	65.75	48
Length	7.39	7.39	6.27	4.17	4.62	3.64	8.18	7.63
Circumference	30.59	30.59	26.77	15.57	18.98	14.26	32.02	27.13
Roughness	1.08	1.08	1.08	0.03	1.09	0.03	1.1	0.03
Transparency	0.12	0.12	0.12	0.08	0.12	0.09	0.15	0.09
Volume (ESD)	404	404	196	695	115	804	910	8228
Breadth	4.74	4.74	4.07	2.16	2.96	1.88	5.17	4.87

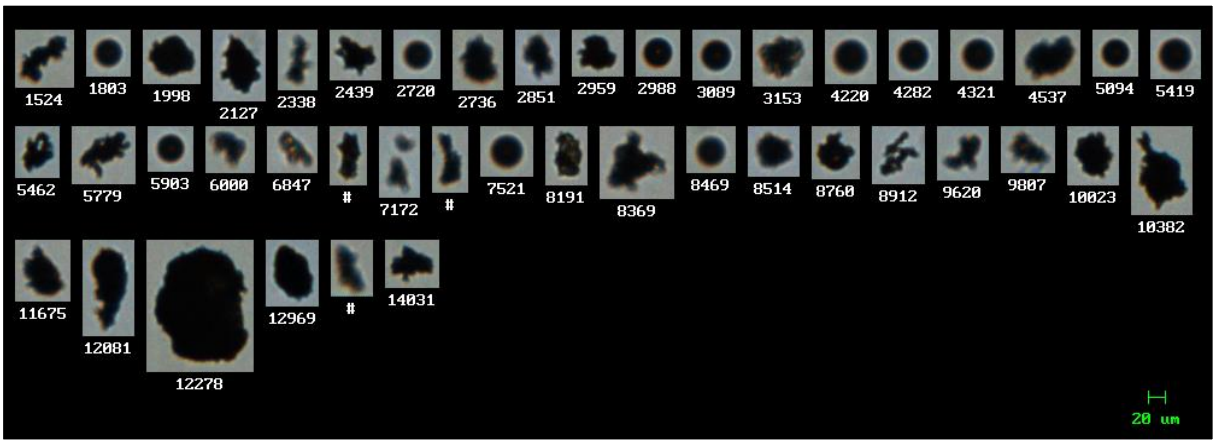
Out 38 24h



Out 41 24h

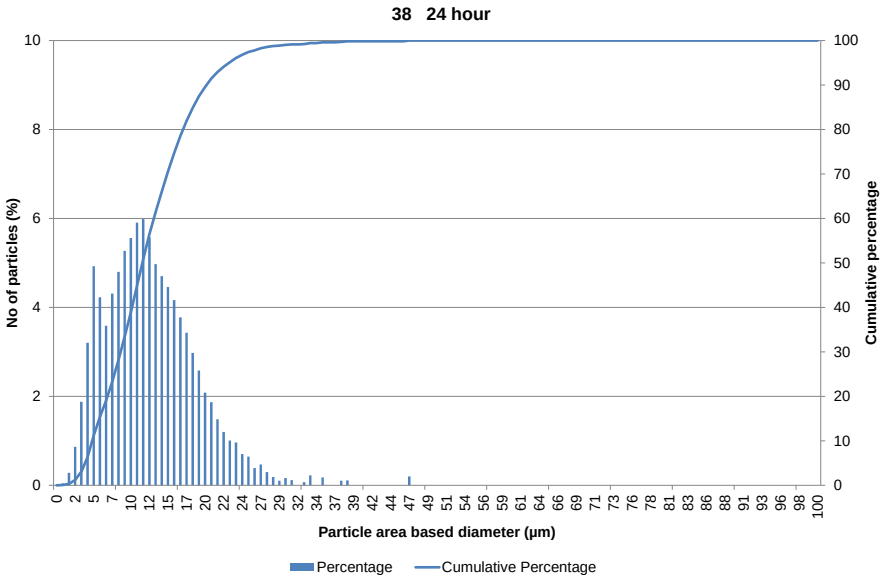


Out 17 24h



Out C 24h

Figure 36. Examples of digital images of individual particles from various cuttings samples after 24 hours of sedimentation.



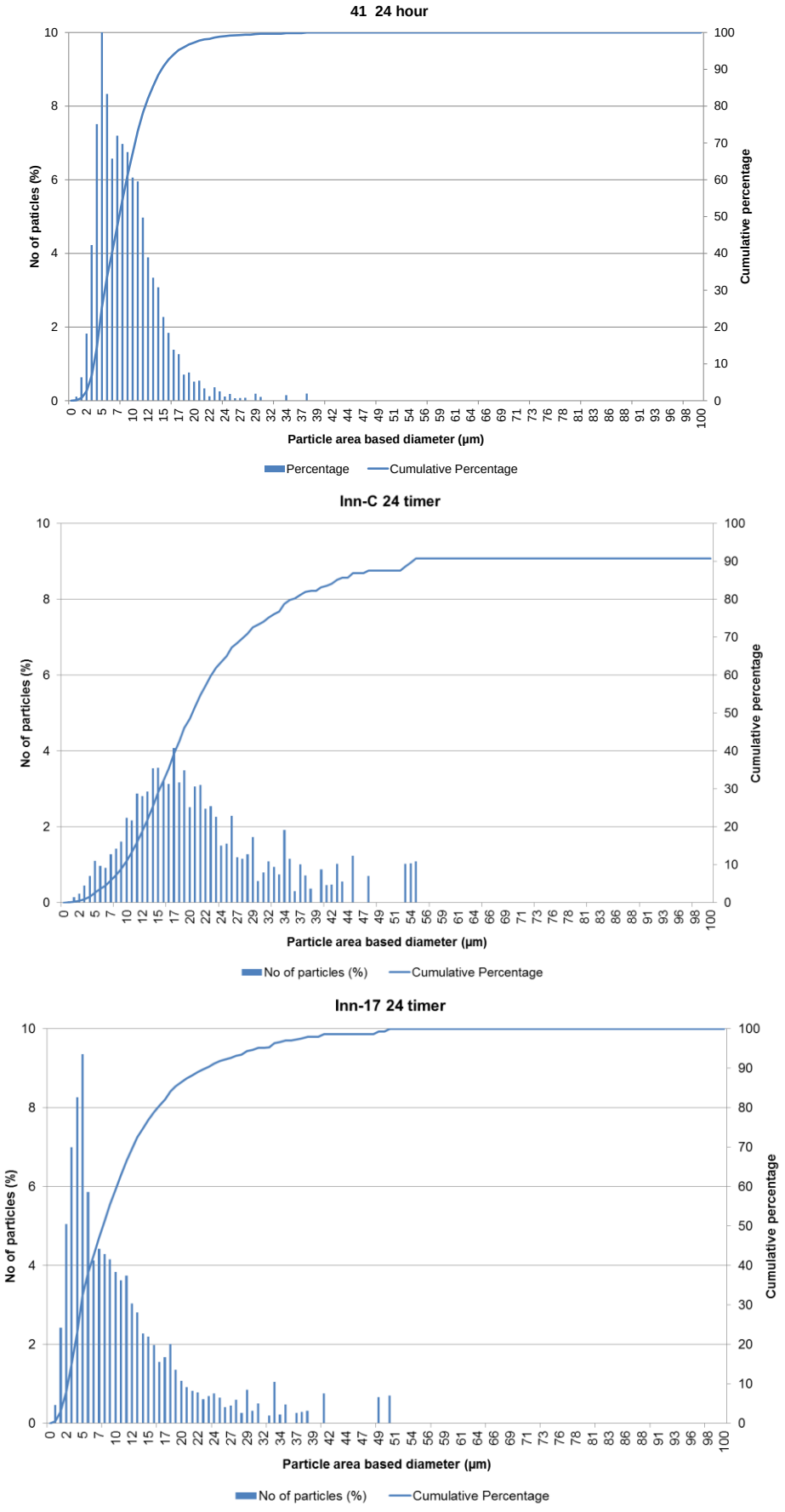
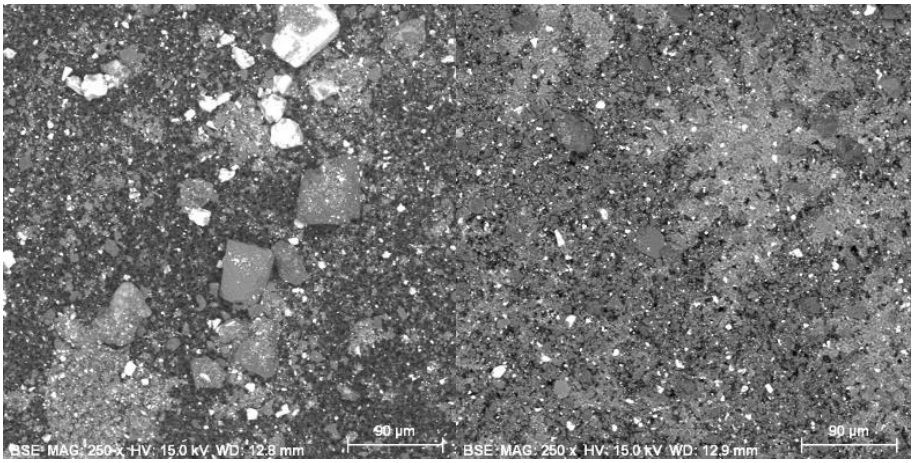


Figure 37. PSD of cuttings samples after 24 hours of sedimentation with FlowCam.

5.4.5. Electron microscopy

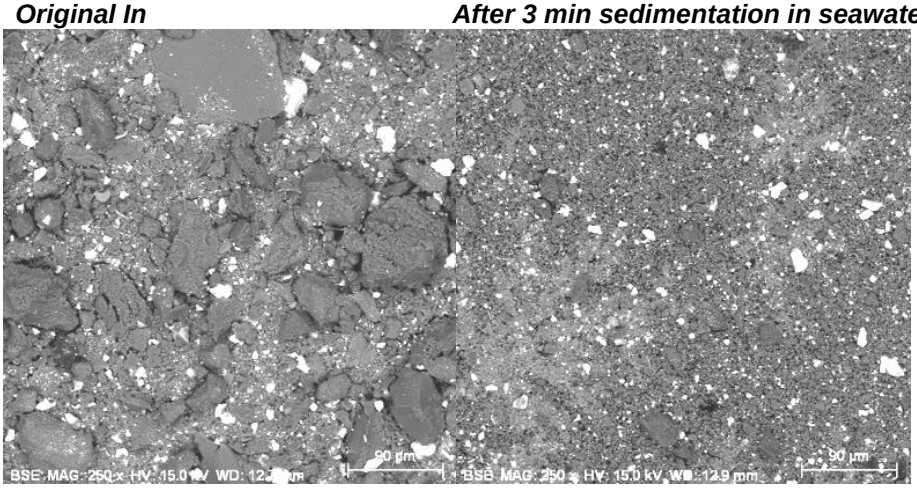
The eight samples investigated are shown in 250 x amplification in Figure 38. This shows that the original samples comprise both large and small particles. Some of the large particles have edges and resemble small stones. There is also a lot of very fine, dust-like material. The light-coloured particles indicate heavier elements such as barium. All four of the original samples resemble each other. The difference between the original samples and the samples after sedimentation is the absence of large particles in the latter group. The average particle size has been reduced, and small particles dominate the picture. The four samples also resemble each other after sedimentation.

17



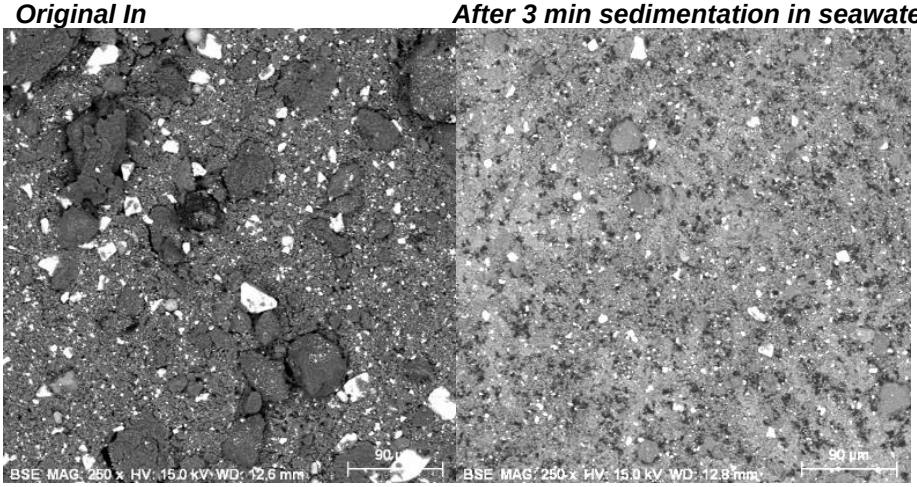
Original In ***After 3 min sedimentation in seawater***

38



Original In ***After 3 min sedimentation in seawater***

41



Original In ***After 3 min sedimentation in seawater***

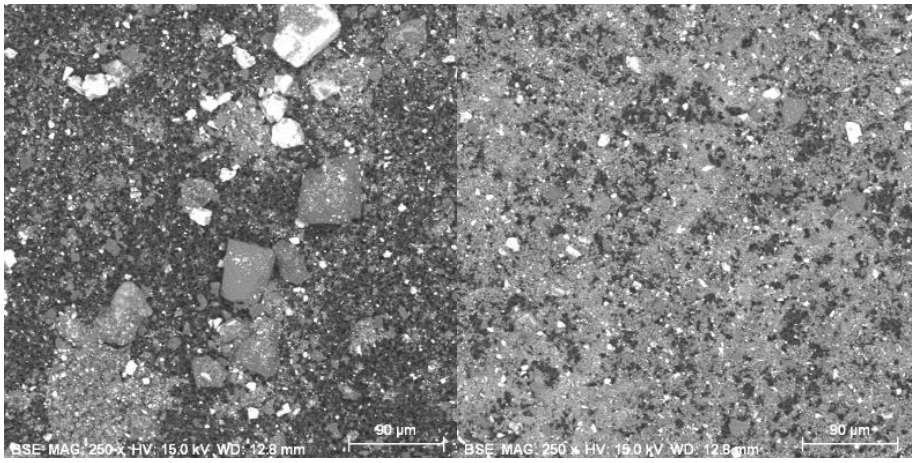


Figure 38. Electron microscope images of the four In cuttings samples and after 3 min sedimentation. Left: original samples. Right: after three minutes of sedimentation in seawater. Sample numbers are listed in the left-hand column (Photo: N. Aas, Statoil).

5.5. Toxicity

5.5.1. Leachate

Results from testing with bacteria (Mara and Microtox), algae (*Skeletonema costatum*) and crustaceans (*Acartia tonsa*) are collated in Table 21. Dose response curves for *Skeletonema costatum* and *Acartia tonsa* are presented in the appendix and all endpoints for these tests are brought together in Table 22.

The results show that leachate from three of the samples had substantial effects on *Skeletonema* (EC_{50} < 20 per cent). This means exposure of *Skeletonema* to 20 per cent of the leachate (a solution of 1: 5) caused growth to cease for 50 per cent of the alga. No effect was identified for sample 17 (EC_{50} > 100 per cent), even with exposure to 100 per cent of the leachate. Sample 17 contained a lower concentration of copper (Cu) than the other samples. This indicates that copper could explain the toxicity for *Skeletonema*. Copper is generally toxic for algae.

Table 21. Acute toxicity in leachate from four samples of treated cuttings. The result for each organism in Mara is presented in figure 39. (The figures in brackets are the weight of cuttings used to prepare the test solution.)

Sample	Mara	Microtox	*Skeletonema*	*Acartia tonsa*
	Average MTC[1]	EC_{50} 15 min	EC_{50} 72 hours	LC_{50} 48 hours
Out 38	68 % (68 g/l)	80 % (80 g/l)	18 % (18 g/l)	>100 % (>100 g/l)
Out 41	66 % (60 g/l)	>100 % (>100 g/l)	18 % (18 g/l)	>100 % (>100 g/l)
Out 17	63 % (63 g/l)	> 100 % (>100 g/l)	100 % (100 g/l)	>100 % (>100 g/l)
Out C	44 % (44 g/l)[2]	53 % (53 g/l)	15 % (15 g/l)	>100 % (>100 g/l)

[1] Microbial toxic concentration (equivalent to EC_{50}).
[2] Caution should be shown in interpreting this value, since only six of the 11 organisms are included in the calculation.

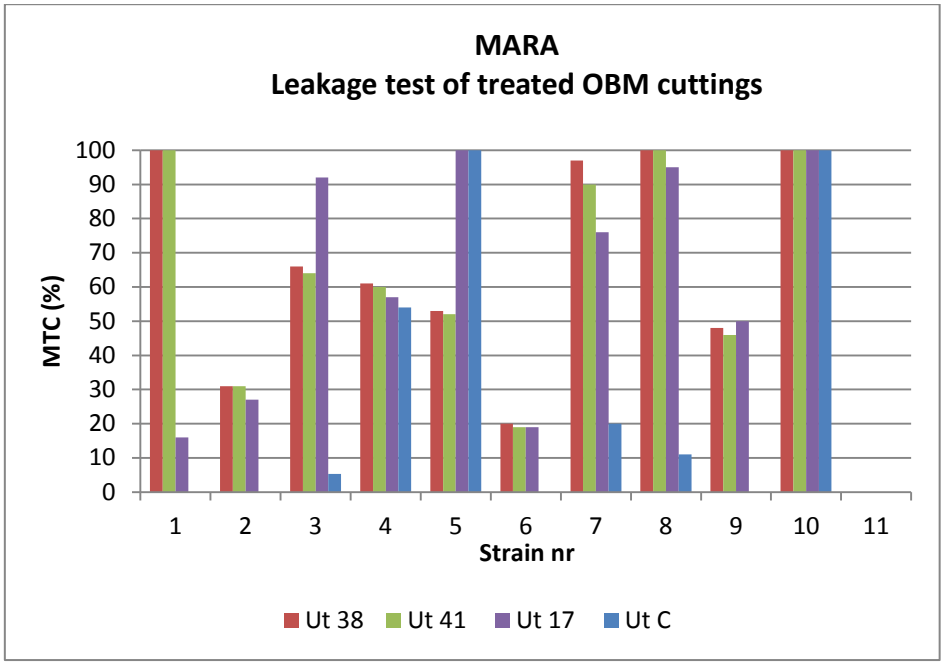


Figure 39. Mara results for each organism (all samples). Measured on leachate.

Table 22. All endpoint results for acute toxicity for Skeletonema costatum and Acartia tonsa in leachate. D=dosage and not concentration (C).

Sample	Endpoint	*Skeletonema costatum*	*Acartia tonsa*	
		72 hours	24 hours	48 hours
Out 38	NOEC	10%	25%	25%
	L(E)D10	12%	>100%	44%
	L(E)D50	18%	>100%	>100%
	L(D)D90	23%	>100%	>100%
Out 41	NOEC	10%	100%	25%
	L(E)D10	12%	>100%	44%
	L(E)D50	18%	>100%	>100%
	L(D)D90	23%	>100%	>100%
Out 17	NOEC	10%	100%	100%
	L(E)D10	78%	>100%	>100%
	L(E)D50	>100%	>100%	>100%
	L(D)D90	>100%	>100%	>100%
Out C	NOEC	2.5%	100%	25%
	L(E)D10	11%	>100%	50%
	L(E)D50	15%	>100%	>100%
	L(D)D90	24%	>100%	>100%

The leachate showed lower toxicity for bacteria and very low for crustaceans (*Acartia*). By comparison, the Swedish Environmental Protection Agency (1996) classifies the toxicity of industrial discharges as follows:

High toxicity: L(E)D50 < 10 vol %
Slightly toxic: 10 vol % > L(E)D < 70 vol %
Low toxicity: L(E)C50 > 70 vol %.

In other words, had this been an industrial discharge from an onshore facility, it would have been classified as a low toxicity discharge with respect to bacteria and crustacean for all samples. For Out 38, 42 and 17, it would be characterised as slightly toxic with respect to algae.

5.5.2. Particles in the water column

The test is conducted with filter-feeding organisms living in the water column: *Calanus finmarchicus* (copeod). The results are collated in Table 23.

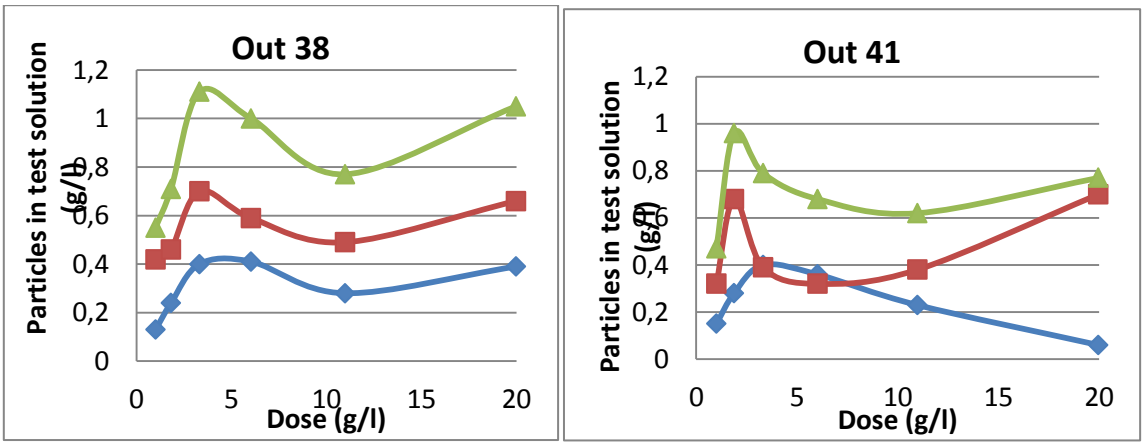
Testing toxicity with *Calanus finmarchicus* aims to determine how far the presence of particles in the water column could increase toxicity compared with tests conducted without particles present. The *Calanus finmarchicus* tests have been carried out with and without particles present.

Calanus finmarchicus exposed to particles were observed to have particles in the gut at the lowest loads. No particles were found in the gut at higher loads, which indicates that the organism is unable to maintain normal filtration activity (all the photographs are reproduced in the appendix).

Table 23. Acute toxicity (based on normal dose) of treated cuttings on filter-feeding organisms (Calanus finmarchicus, 96 hours).

Sample	Without particles		With particles	
	LD_{50}	LD_{10}	LD_{50}	LD_{10}
Out 38	>20 g/l	>20 g/l	8 g/l	5 g/l
Out 41	>20 g/l	>20 g/l	20 g/l	13 g/l
Out 17	18 g/l	14 g/l	4 g/l	2.1 g/l
Out C	>25 g/l	>25 g/l	15 g/l	1.4 g/l

The reported concentration is the nominal dose. Since a proportion of the particles had sedimented before exposure, the concentration of particles which the organisms were exposed to was lower than the nominal dose. Measuring particles with the Coulter Counter, which measures from 1.2-70 µm, shows no unambiguous relationship between the dose and measured particle content in samples Out (Ut) 38 and Out 41 (Figure 40). Flocculation caused faster sedimentation with higher concentrations. Figure 41 shows that no clear response curve can be established on the basis of measured particles in the solutions. As a result, LC_{50} and LC_{10} have not been calculated for measured particle concentrations in the exposure solution.



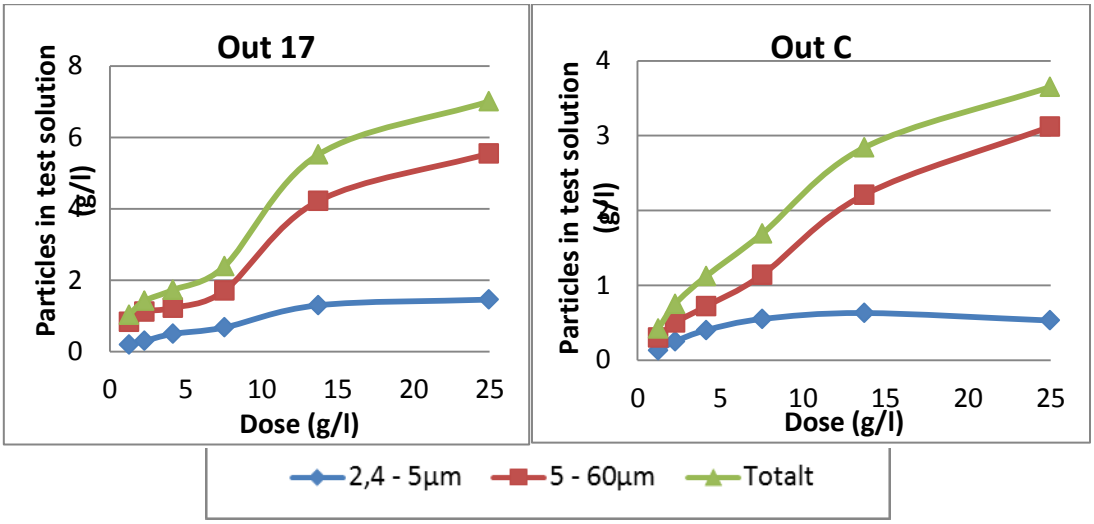


Figure 40. Analysis of particles in solutions to which Calanus finmarchicus was exposed in samples with particles.

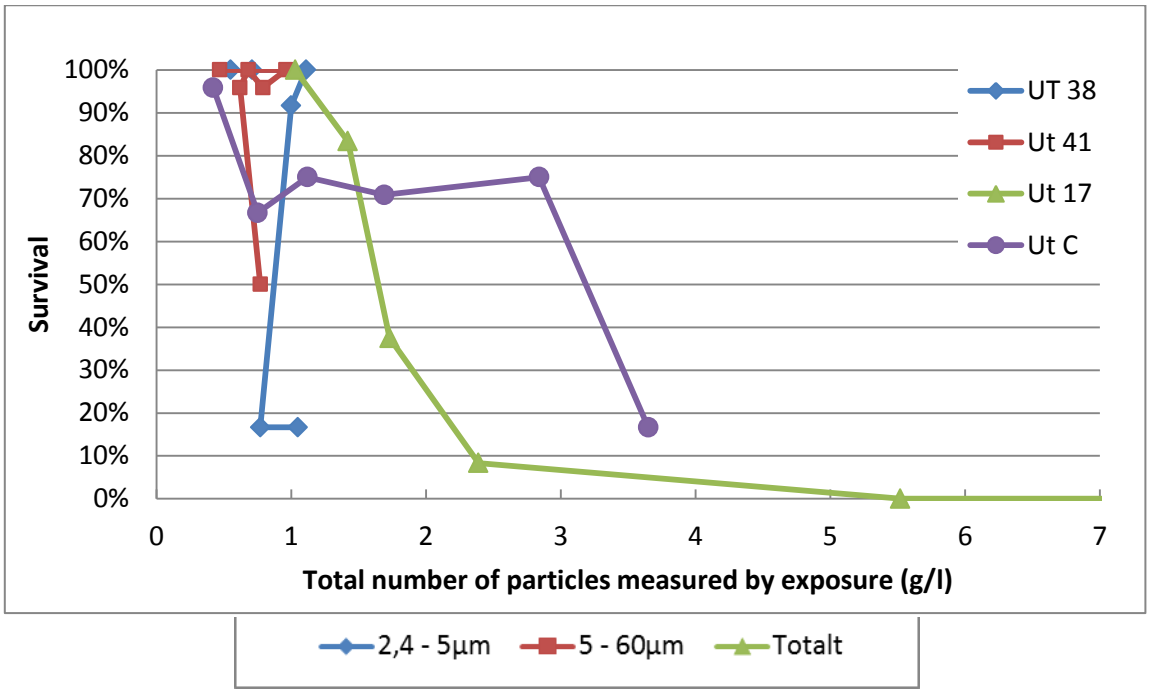
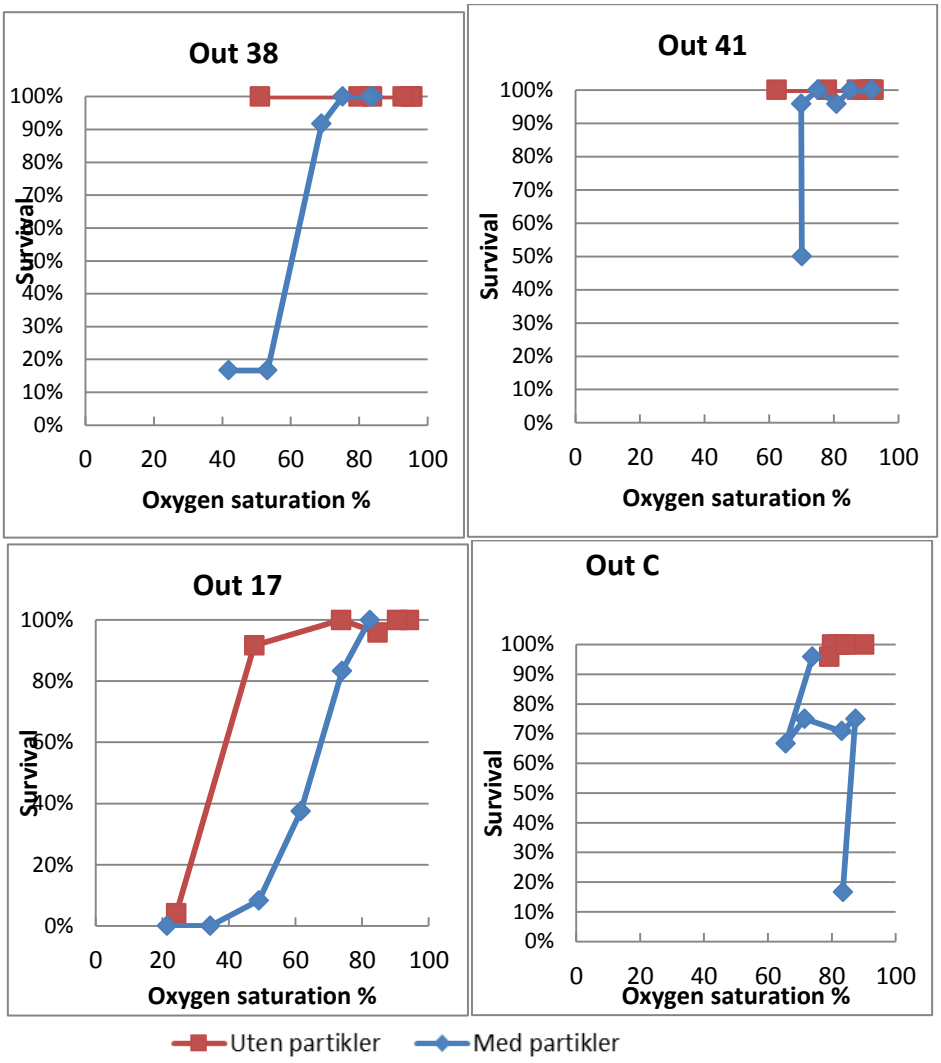


Figure 41. Survival related to the measured quantity of particles in samples with particles.

Oxygen and pH were also measured in the solutions. All the samples provided an alkaline solution, with a pH varying between 8.1 and 9.2. Reduced oxygen content was observed in all test solutions at 96 hours, the end of the exposure time. This reduction is far above the amount of oxygen that the biomass could manage to consume in that time and it must accordingly be attributed to chemical processes in the solutions. Figure 42 shows that the toxic effect could be caused by oxygen deficiency. It is not known what variations of pH and oxygen can be tolerated by *Calanus finmarchicus*, but it is conceivable that the toxic effect is due either to oxygen deficiency or increased pH taking place in the samples during the test.



Key: Uten partikler = Without particles; Med partikler = With particles

Figure 42. Survival in relation to oxygen saturation for all samples.

5.5.3. Toxicity of the sediment

Tests have been conducted with sediment-dwelling organisms: *Corophium volutator*. This is a 10-day test. Its results indicate how far toxic effects can be expected on the seabed with sedimentation on the likely scale. The figures are collated in Table 24.

Table 24. Acute toxicity from treated cuttings for sediment-dwelling organisms (Corophium volutator, 10 days).

Sample	LD_{50}	LD_5	NOEC
Out 38	50%	Not calculated	25%
Out 41	63%	Not calculated	25%
Out 17	> 100	26%	8%
Out C	about 100%	25%	<8%

BioTrix observed no reworking of the cuttings in the sediment at the two highest exposure concentrations (50 and 100 per cent) of samples Out 17 and Out C. No reworking activity was observed in 26 per cent of the cuttings in the sediment. Activity was close to the normal determined in the control flasks, at eight and 14 per cent of cuttings in the reference sediment.

6. Environmental risk assessment

6.1. PNEC values

Many different values for the PNEC (Predicted No Effect Concentration) are found in the literature. Emphasis is given to using official values where these exist (the EU, the Norwegian Environment Agency and so forth). Where they are not available, conservative (low) values have been chosen where doubt has arisen about which to use.

The Norwegian Environment Agency's values (TA 3001-2012, Weideborg *et al*, 2012) are primarily based either on EU-RAR or quality standard (QS) values from the EU's framework directive for coastal waters. These have not been specifically prepared for seawater (marine systems). PEC/PNEC calculations for sediments are based on PNEC values from the Norwegian Environment Agency and Altin (supplemented with background values).

For substances where such values have not been available, we have utilised values from the literature and made assessments based on the EU's guide for marine risk assessment (EU, 2003). Table 25 presents selected PNEC and EC_{50} values used in the calculations. References for these are provided below.

Barium
Barium values were discussed in chapter 3. The PNEC and EC_{50} water are taken from Brakstad *et al* (2006). The PNEC sediment is taken from Altin *et al* (2008).

Metals
EC_{50} and PNEC values from the Norwegian Environment Agency (Weideborg *et al*, 2012) are used for water. Altin *et al* (2008) proposes PNEC values for six metals (zinc, copper, nickel, cadmium, lead and mercury) for both water and sediments. This assessment proposes $PNEC_{water}$ in the order of magnitude of the earlier values from the SFT (Norwegian Environmental Agency, 2007) and Weideborg et al (2012). The revision of these was based on the availability of newer toxicity data. As a result, the Norwegian Environment Agency's PNEC for water is to be preferred.

It was decided to conduct two assessments for sediment, as described in chapter 3. One is based on the official values from the Norwegian Environment Agency and the other on more field-specific values from Altin *et al* (2008) supplemented by background values.

PAH
EC_{50} and PNEC values from the Norwegian Environment Agency (Weideborg *et al*, 2012) are used, with EQS dossiers (EU, 2011) being utilised for naphthalene, anthracene, fluoranthene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[ghi]perylene and indeno[1,2,3-cd]pyrene. The evaluation of PAH_{16} from the EU's risk assessment of PAH in coal-tar pitch (ECHA, 2011) was also used.

We have calculated the PNEC for heavy metals and PAH in accordance with the methodology in the technical guidance document for deriving environmental quality standards, common implementation strategy for the water framework directive (2000/60/EC) – Guidance document no 27 (TGD no 27). The background values are taken from OSPAR (2006). Where sediments are concerned, the PNEC from Altin *et al* (2008) was also used for comparison.

Aliphatic hydrocarbons
Finding good values for hydrocarbon toxicity is difficult. Most tests have been conducted with oil fractions containing both aliphatic and aromatic hydrocarbons, rather than with individual components. The values proposed by OSPAR (2012) are used. No official value exists for

sediments. Use can be made of a $PNEC_{sediment}$ derived from $PNEC_{water}$ using the formula from the EU's TGD:

$$PNECsediment = PNECwater * K_d$$

where Kd is the sediment-water distribution coefficient, which is estimated as

$$K_d = K_{oc} * f_{oc}$$

where f_{oc} is the fraction of organic carbon in the sediment

$f_{oc} = 1\%$ (used in preparing the Norwegian EQS)

And K_{oc} is the distribution coefficient between organic carbon and water taken from the risk assessment for polluted ground (Weideborg and Vik, 2007):

Koc for	THC C_5-C_8:	1 252	(geometric average of values for C_5-C_6 and C_6-C_8)
	THC C_8-C_{10}:	32 000	
	THC C_{10}-C_{12}:	250 000	
	THC C_{12}-C_{16}:	5 000 000	
	THC C_{16}-C_{35}:	10 000 000	

Alternatively, data from Altin et al (2008) can be used. Only one value (318.5 mg/kg dm) then applies for the total of aliphates, and aliphatic fractions are not used.

Table 25. Collation of background data from determining PNEC values and TU.

Substance	Background value seawater (µg/l)	EC_{50} water (µg/l)	PNEC seawater (µg/l)	Background value sediment (mg/kg)	PNEC sediment (mg/kg dm)	
					EQS/ Ospar	Altin et al, 2008
Barium	no data	20000	200	no data	-	848
Metals:						
Arsenic	0.15	85	4.8	15	47	-
Lead	0.05	57	1.2	25	150	21.6
Cadmium	0.03	1.48	0.21	0.2	2.5	0.077
Mercury	0.001	0.7	0.05	0.05	0.52	8.23
Copper	0.3	5.2	2.6	20	84	24.68
Chromium	0.2	358	3.4	60	620	0.125
Zinc	1.5	60	3.4	90	340	-
Nickel	0.5	67	8.6	30	43	41.86
PAH:						
Naphthalene	0.00061	650	2	0.002	0.027	2.05
Acenaphthylene	0.00001	330	1.3	0.0016	0.033	-
Acenaphthene	0.01	580	3.8	0.0024	0.16	-
Fluorine	0.00019	500	2.5	0.0068	0.26	-
Phenanthrene	0.00025	51	1.3	0.0024	0.5	-
Anthracene	0.004	1	0.1	0.0024	0.0048	-
Fluoranthene	0.00029	0.6	0.12	0.008	0.117	-
Pyrene	0.000053	0.23	0.023	0.0052	0.014	-
Benzo[a]anthracene	0.01	1.8	0.012	0.0036	0.06	-
Chrysene	0.01	0.7	0.07	0.0044	0.28	-
Benzo[b]fluoranthene	0.01	1.7	0.017	0.09	0.14	-
Benzo[k]fluoranthene	0.01	1.7	0.017	0.09	0.14	-
Benzo[a]pyrene	0.01	2.7	0.022	0.006	0.18	-
Indeno[1,2,3-cd]pyrene	0.002	0.27	0.00027	0.02	0.063	-

Dibenzo[a,h]anthracene	0.01	1.8	0.001	0.012	0.027	-
Benzo[ghi]perylene	0.002	0.2	0.008	0.018	0.084	-
2-3 ring PAH	-	-	-	-	-	0.11
4+ ring PAH	-	-	-	-	-	0.4
Aliphatic hydrocarbons						
Total aliphatics	no data	1000	70	-	-	318.5
$>C_5$-C_8	no data	1000	70	no data	1.25	-
$>C_8$-C_{10}	no data	1000	70	no data	22.4	-
$>C_{10}$-C_{12}	no data	1000	70	no data	175	-
$>C_{12}$-C_{16}	no data	1000	70	no data	3500	-
$>C_{16}$-C_{35}	no data	1000	70	no data	7000	-

6.2. Leaching of pollution to the water column

6.2.1. Environmental standard

Classification of leachate is presented in Table 26. Were the leachate to be classed as coastal water, all the samples would have to be classified as red (very poor) because of the copper content. The detection limit for many substances – all PAH, arsenic, lead, cadmium and mercury – is higher than the background value, and class 1 (Background) cannot be used even if the substance has not been identified.

Table 26. Analysis of PAH and metals in leachate. The colour code is for seawater quality in coastal waters. Blue = background, green = good, yellow = moderate, orange = poor and red = very poor (Weideborg et al 2012).

Analysis parameter (µg/l)	Carbonate Out (38)	Clay Out (41)	Clay Out (17)	Cuxhaven Out (C)
PAH_{16}				
Naphthalene	0.33	0.06	0.15	0.092
Acenaphthylene	<0.01	<0.01	<0.01	<0.01
Acenaphthene	<0.01	<0.01	<0.01	<0.01
Fluorine	<0.01	<0.01	<0.01	<0.01
Phenanthrene	0.014	0.014	0.016	<0.01
Anthracene	<0.01	<0.01	<0.01	<0.01
Fluoranthene	<0.01	<0.01	<0.01	<0.01
Pyrene	<0.01	<0.01	<0.01	<0.01
Benzo[a]anthracene	<0.01	<0.01	<0.01	<0.01
Chrysene/triphenylene	<0.01	<0.01	<0.01	<0.01
Benzo[b]fluoranthene	<0.01	<0.01	<0.01	<0.01
Benzo[k]fluoranthene	<0.01	<0.01	<0.01	<0.01
Benzo[a]pyrene	<0.01	<0.01	<0.01	<0.01
Indeno[1,2,3-cd]pyrene	<0.002	<0.002	<0.002	<0.002
Dibenzo[a,h]anthracene	<0.01	<0.01	<0.01	<0.01
Benzo[ghi]perylene	<0.002	<0.002	<0.002	<0.002
Metals				
Arsenic	2.60	2.3	16	< 1
Lead	0.71	0.31	< 0.2	0.26
Cadmium	< 0.2	< 0.2	< 0.2	< 0.2
Copper	59	46	17	26
Chromium	9	10	2.4	3
Mercury	< 0.05	< 0.05	0.08	< 0.05
Nickel	46	40	46	45
Zinc	3.20	3.1	10	6.1

This assessment indicates that only certain metals pose an environmental risk in leachate. Neither barium nor aliphatic hydrocarbons have been evaluated in the EQS. These must nevertheless be included in the environmental risk assessment.

When classifying in accordance with the EQS, no account has been taken of the dilution of treated OBM cuttings when discharged and dispersed over a wide area. This is taken into account in a risk assessment.

6.2.2. Comparison of calculated and measured toxicity in leachate

A theoretical calculation of acute toxicity in leachate has been conducted in accordance with The Norwegian Agency's Guide for ecotoxicological studies of industrial discharges (Norwegian Environmental Agency, 2000). This has been done to be able to compare the results from the toxicity tests conducted with the theoretical $L(E)C_{50}$ for the water blend, calculated on the basis of the chemical characteristics of the discharge water. The method assumes that the various substances will have an additive toxic effect. TUs for each substance in the blend (TU_{blend}) are summed.

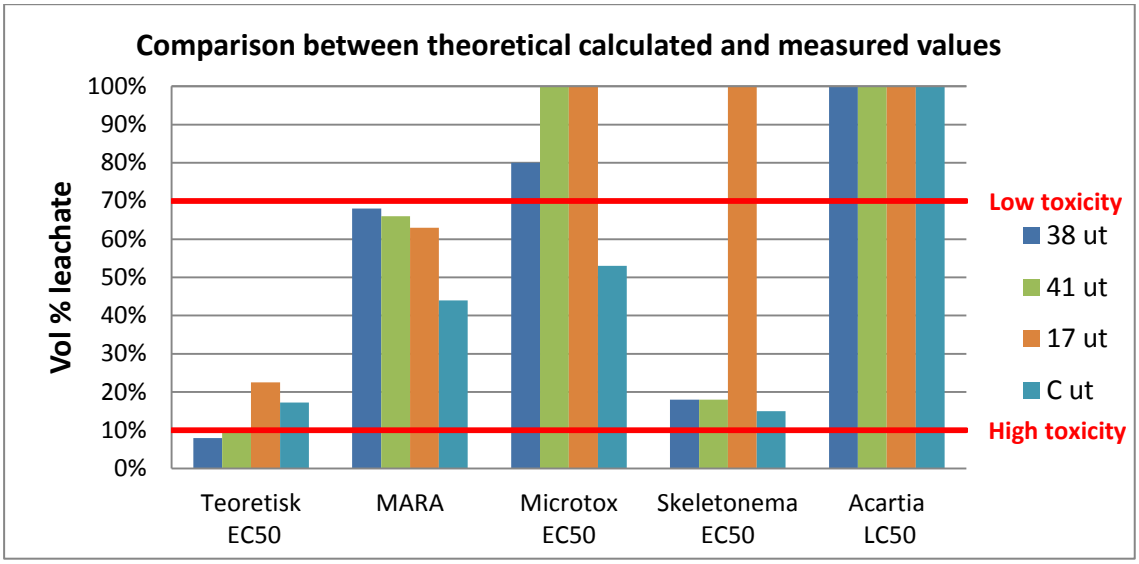
The results from measurements of leachate are checked against the measured toxicity of the same water. The TU equals the measured concentration divided by the literature value for the lowest LC_{50} value. Acute toxicity is used as the basis for calculating the TU because this is what has also been measured in toxicity measurements of the discharge water. The leachate's theoretical acute toxicity (percentage leachate in the recipient) is then $100/TU_{blend}$ (volume per cent). The result of the theoretical calculation is compared with measurements made with the following organisms:

- Microorganisms (Microtox and MARA)
- Algae (*Skeletonema costatum)*
- Crustacean in the water phase (*Acartia tonsa*).

According to the Swedish Environmental Protection Agency (1996), industrial waste water is considered to have low toxicity when organisms can be exposed to 70 per cent of the water without reaching 50 per cent mortality. It is considered to have high toxicity if 50 per cent of the organisms die when they are exposed to 10 per cent of the leachate. On the basis of this definition, leachate from the cuttings samples has low toxicity when measured toxicity in bacteria and crustaceans alone is taken into account.

Table 27 presents an overview of measured EC_{50} and calculated TU for the priority pollutants found in the leachate, compared with measured values. Calculated toxicity is higher measurements from our toxicity tests. According to the calculation, leaching from samples is classified as high toxicity. Copper is the substance which makes the contribution to the toxicity of the leachate. The results are also presented graphically in

Figure 43. The theoretically calculated EC_{50} is in the same order of magnitude as the lowest measured EC_{50} in the *Skeletonema* test. This suggests that we have identified the substances which account for most of the toxicity of the leachate. Obtaining exactly the same value for the lowest $L(E)C_{50}$ from theoretical calculations and tests cannot be expected.



Key: Teoretisk = Theoretical

Figure 43. Comparison between calculated toxicity in leachate and measured toxicity from various toxicity tests.

Table 27. Toxicity units (TU) calculated for priority pollutants in leachate from cuttings compared with measured toxicity. Concentrations <LQL are set at zero to avoid giving excess weight to substances not identified in the samples.

Analysis parameter (µg/l)	EC_{50} (µg/l)	TU			
		Out 38	Out 41	Out 17	Out C
Oil					
THC (>5-35)	1 000	0.42	0.38	0.07	0.04
PAH					
Naphthalene	650	0.0005	0.0001	0.0002	0.0001
Acenaphthylene	330	0	0	0	0
Acenaphthene	580	0	0	0	0
Fluorine	500	0	0	0	0
Phenanthrene	51	0.0003	0.0003	0.0003	0
Anthracene	1	0	0	0	0
Fluoranthene	0.6	0	0	0	0
Pyrene	0.23	0	0	0	0
Benzo[a]anthracene	1.8	0	0	0	0
Chrysene/triphenylene	0.7	0	0	0	0
Benzo[b]fluoranthene	1.7	0	0	0	0
Benzo[k]fluoranthene	1.7	0	0	0	0
Benzo[a]pyrene	2.7	0	0	0	0
Indeno[1,2,3-cd]pyrene	0.27	0	0	0	0
Dibenzo[a,h]anthracene	1.8	0	0	0	0
Benzo[ghi]perylene	0.2	0	0	0	0
Metals					
Arsenic	85	0.031	0.027	0.19	0
Barium	20 000	0.006	0.005	0.007	0.007
Lead	57	0.012	0.005	0	0.0046
Cadmium	1.48	0	0	0	0
Copper	5.2	11.3	8.8	3.3	5.0
Chromium	358	0.025	0.028	0.007	0.008
Mercury	0.7	0	0	0.11	0
Nickel	67	0.69	0.60	0.69	0.67
Zinc	60	0.05	0.05	0.17	0.10

Toxicity parameter	TU			
	Out 38	Out 41	Out 17	Out C
Total TU_{blend}	**13**	**10**	**4**	**6**
100/TU (vol%) theoretical calculated:	**7**	**8**	**10**	**23**
Acartia measured toxicity (%)	>100	>100	>100	>100
Skeletonema measured toxicity (%)	**18**	**18**	100	**15**
Microtox measured toxicity (%)	80	>100	>100	53
MARA measured toxicity (%)	68	66	**63**	**44**

6.2.3. PEC/PNEC calculations

The SINTEF modelling shows a maximum concentration in the water column of 1-5 mg/l. Our leachate had a concentration of 0.1 kg/l, and accordingly had to be diluted 20 000 times to correspond to the highest expected environmental concentration of 5 mg/l. When calculating environmental risk (PEC/PNEC ratio), the decision was taken to conduct a calculation based on the leachate without dilution in the recipient and with the above-mentioned dilution of 20 000. Table 28 presents an overview of calculated PEC/PNEC for the priority pollutants identified in leachate from treated cuttings.

Table 28. PEC/PNEC calculations of the priority pollutants identified in leachate from treated OBM cuttings.

Analytical parameter	PNEC (µg/l)	Concentration/PNEC leachate (No dilution)				PEC/PNEC seawater (mg/kg) (dilution 1 : 20 000)			
		Out 38	Out 41	Out 17	Out C	Out 38	Out 41	Out 17	Out C
Oil									
THC	70	**6.00**	**5.43**	0.97	0.59	3E-04	3E-04	<5E-05	3E-05
PAH_{16}									
Naphthalene	2	0.165	0.03	0.08	0.05	8E-06	2E-06	4E-06	2E-06
Acenaphthylene	1.3	<0.008	<0.008	<0.008	<0.008	<4E-07	<4E-07	<4E-07	<4E-07
Acenaphthene	3.8	<0.003	<0.003	<0.003	<0.003	<1E-07	<1E-07	<1E-07	<1E-07
Fluorine	2.5	<0.004	<0.004	<0.004	<0.004	<2E-07	<2E-07	<2E-07	<2E-07
Phenanthrene	1.3	0.011	0.011	0.012	<0.008	5E-07	5E-07	6E-07	<4E-07
Anthracene	0.1	<0.1	<0.1	<0.1	<0.1	<5E-06	<5E-06	<5E-06	<5E-06
Fluoranthene	0.12	<0.08	<0.08	<0.08	<0.08	<4E-06	<4E-06	<4E-06	4E-06
Pyrene	0.023	<0.4	<0.4	<0.4	<0.4	<2E-05	<2E-05	<2E-05	<2E-05
Benzo[a]anthracene	0.012	<0.8	<0.8	<0.8	<0.8	<4E-05	<4E-05	<4E-05	<4E-05
Chrysene/triphenylene	0.07	<0.1	<0.1	<0.1	<0.1	<7E-06	<7E-06	<7E-06	<7E-06
Benzo[b]fluoranthene	0.017	<0.6	<0.6	<0.6	<0.6	<3E-05	<3E-05	<3E-05	<3E-05
Benzo[k]fluoranthene	0.017	<0.6	<0.6	<0.6	<0.6	<3E-05	<3E-05	<3E-05	<3E-05
Benzo[a]pyrene	0.022	<0.5	<0.5	<0.5	<0.5	<2E-05	<2E-05	<2E-05	<2E-05
Indeno[1,2,3-cd]pyrene	0.0027	<0.7	<0.7	<0.7	<0.7	<4E-05	<4E-05	<4E-05	<4E-05
Dibenzo[a,h]anthracene	0.001	<10	<10	<10	<10	<5E-04	<5E-04	<5E-04	<5E-04
Benzo[ghi]perylene	0.008	<0.25	<0.25	<0.25	<0.25	<1E-05	<1E-05	<1E-05	<1E-05
Metals									
Arsenic	4.8	0.54	0.48	3.33	<0.21	3E-05	2E-05	2E-04	<1E-05
Barium	200	0.55	0.47	0.70	0.70	3E-05	2E-05	4E-05	4E-05
Lead	1.2	0.59	0.26	<0.2	0.22	3E-05	1E-05	8E-06	8E-06
Cadmium	0.21	<1	<1	<1	<1	<5E-05	<5E-05	<5E-05	<5E-05
Copper	2.6	**23**	**18**	**6.5**	**10**	1E-03	9E-04	3E-04	5E-04
Chromium	3.4	**3**	**3**	0.7	0.9	1E-04	1E-04	4E-05	4E-05
Mercury	0.05	<1	<1	**1.6**	<1	<5E-05	<5E-05	8E-05	<5E-05
Nickel	8.6	5.3	4.7	5.3	5.23	3E-04	2E-04	3E-04	3E-04

The PEC/PNEC is a measure of environmental risk – in other words, whether a given discharge of a substance has a negative effect on the environment. If the PEC/PNEC is > one, the environmental risk is unacceptable pursuant to the EU's Guidelines. A dilution of 20

000 means that all concentrations (PECs) will be far lower than the PNEC. The environmental risk based on leachate is expected to be negligible.

6.3. Particles in the water column

When discharging treated OBM cuttings (samples Out 38, 41, C and 17), the environmental risk in the water column could be attributable to three different factors:

- The toxicity of leachate
- Physical factors
- Consumption of small particles which have a toxic effect or fill the gut and prevent further uptake of nutrients.

Leaching of toxicity presents no risk. To take account of the possibility that filter-feeding organisms will consume particles, however, an adjusted PEC/PNEC can be calculated for all chemical components – including those still appended to cuttings. Analysing the morphology of the particles shows that treatment of the cuttings produces rounded particles. Testing of *Calanus finmarchicus* demonstrated effects from consumption of particles.

6.3.1. PEC/NEC calculations

A PEC/PNEC for all chemical substances in measured in treated OBM cuttings in suspension in the water is a "worst case" calculation, since it assumes that all these substances are available to organisms. The calculation was done for 5 ppm in the water. SINTEF's modelling shows that a maximum of 1-5 ppm of cuttings could be found in the water column. The results are shown in Table 29. The PEC/PNEC for chemical substances in particles is higher than those calculated for leachate because part of the substances are adsorbed in the cuttings, but all PEC/PNECs still remain << 1.

Table 29. PEC/PNEC calculations at five ppm cuttings in the water column for the priority pollutants found in treated cuttings.

Analytical parameter	PNEC (µg/l)	Concentration at five ppm cuttings in the water column (mg/l)				PEC/PNEC at five ppm cuttings in the water column			
		Out 38	Out 41	Out 17	Out C	Out 38	Out 41	Out 17	Out C
Oil									
THC	70	7.5E-02	1.4E-02	2.2E-02	4.3E-03	0.0011	0.0019	0.0031	0.0006
PAH_{16}									
Naphthalene	2	<2E-09	<2E-09	1.3E-06	1.5E-07	1.3E-08	1.3E-08	6.3E-06	7.3E-07
Acenaphthylene	1.3	<2E-09	<2E-09	5.5E-08	4.0E-08	1.9E-08	1.9E-08	4.2E-07	3.0E-07
Acenaphthene	3.8	<2E-09	<2E-09	9.0E-07	6.5E-08	6.6E-09	6.6E-09	2.4E-06	1.7E-07
Fluorine	2.5	<2E-09	<2E-09	1.2E-07	3.7E-08	1.0E-08	1.0E-08	4.8E-07	1.5E-07
Phenanthrene	1.3	<2E-09	<2E-09	8.5E-07	8.0E-08	1.9E-08	1.9E-08	6.5E-06	6.2E-07
Anthracene	0.1	<2E-09	<2E-09	1.2E-07	1.5E-08	2.5E-07	2.5E-07	1.2E-05	1.5E-06
Fluoranthene	0.12	<2E-09	<2E-09	2.3E-07	4.0E-08	2.1E-07	2.1E-07	1.9E-05	3.3E-06
Pyrene	0.023	<2E-09	<2E-09	4.6E-07	8.5E-08	1.1E-06	1.1E-06	2.0E-04	3.7E-05
Benzo[a]anthracene	0.012	3.0E-08	6.0E-08	1.8E-07	1.1E-07	2.5E-05	5.0E-05	1.5E-04	9.2E-05
Chrysene/triphenylene	0.07	<2E-09	1.2E-08	2.9E-07	1.1E-07	3.6E-07	1.6E-06	4.1E-05	1.5E-05
Benzo[b]fluoranthene	0.017	2.1E-08	7.0E-08	2.3E-07	1.5E-07	1.2E-05	4.1E-05	1.3E-04	8.5E-05
Benzo[k]fluoranthene	0.017	1.1E-08	1.7E-08	1.5E-07	1.0E-07	5.0E-06	7.5E-06	6.6E-05	4.5E-05
Benzo[a]pyrene	0.022	2.0E-08	5.5E-08	1.0E-07	3.7E-07	7.4E-05	2.0E-04	3.7E-04	1.4E-03
Indeno[1,2,3-cd]pyrene	0.0027	1.5E-08	2.2E-08	3.3E-08	1.1E-07	1.5E-04	2.2E-04	3.3E-04	1.1E-03
Dibenzo[a,h]anthracene	0.001	2.1E-08	3.2E-08	6.0E-08	5.0E-07	2.6E-05	3.9E-05	7.5E-05	6.3E-04
Benzo[ghi]perylene	0.008	<0.25	<0.25	<0.25	<0.25	<1E-05	<1E-05	<1E-05	<1E-05

Metals									
Arsenic	4.8	2.0E-05	2.8E-05	4.2E-05	3.9E-05	4.2E-05	5.8E-05	8.8E-05	8.1E-05
Barium	200	3.9E-02	3.5E-02	8.0E-04	2.6E-03	2.0E-03	1.7E-03	4.0E-05	1.3E-04
Lead	1.2	1.4E-04	1.2E-04	1.5E-04	1.1E-04	1.2E-03	9.6E-04	1.3E-03	8.8E-04
Cadmium	0.21	4.0E-07	1.1E-06	6.5E-07	6.5E-07	1.9E-05	5.2E-05	3.1E-05	3.1E-05
Copper	2.6	9.0E-04	2.1E-04	1.3E-04	1.6E-04	3.5E-03	7.9E-04	4.8E-04	6.0E-04
Chromium	3.4	1.2E-04	1.4E-04	1.2E-04	1.1E-04	3.5E-04	4.1E-04	3.5E-04	3.2E-04
Mercury	0.05	3.5E-07	4.4E-07	1.3E-07	4.0E-08	7.0E-05	8.7E-05	2.5E-05	8.0E-06
Nickel	8.6	1.4E-04	1.6E-04	1.3E-04	8.5E-05	1.6E-04	1.8E-04	1.5E-04	9.9E-05
Zinc	3.4	1.0E-03	7.0E-04	2.8E-04	4.3E-04	2.9E-03	2.1E-03	8.1E-04	1.3E-03

6.3.2. *Calanus finmarchicus* and comparison with modelled concentrations

LC_{10} for *Calanus finmarchicus* was measured at one to 13 g/l of cuttings. Since the anticipated environmental concentration (one-five ppm) is expected to be 1 000 times smaller, particles in the water are not expected to pose a risk to pelagic filter-feeding organisms.

6.4. Pollution in sediments

6.4.1. Classification in accordance with environmental standard

Classification of cuttings in accordance with the Norwegian Environment Agency's limit values for classifying sediment was covered in sections 5.2.1 and 5.3.1. The classification of a sample is normally governed by the component which gives the poorest result. Should cuttings end up directly in sediment, without any blending with particles in the sediment and no dispersion over the seabed, virtually all the substances contained would be in the green (good) or blue (background) categories, while certain substances could reduce the classification to a poorer category. The samples are classified as:

- Carbonate (Out 38): orange (poor) because of the copper content
- Shale (Out 41): green (good)
- Shale (Out 17): yellow (moderate) because of the content of naphthalene, acenaphthene, anthracene and pyrene
- Cuxhaven (Out C): orange (poor) because of the content of benzo[ghi]perylene.

6.4.2. PEC/NEC calculations

SINTEF's dispersion modelling calculates a maximum depth of 1.8 mm for cuttings in sediments. The layer of cuttings can blend with the uppermost layer of the sediment where the organisms live – the bioactive layer, where a bioturbation also occurs as various sediment-dwelling organisms rework and mix the sediment. Estimating the thickness of this layer is difficult, but it will vary between 0 and 10 cm. Bioturbation declines gradually with increasing sediment depth. In other words, it will not terminate abruptly at any specific level, but the bulk of the fauna is likely to live in the topmost 5 cm. This is also by and large the depth to which a grab takes samples from an average sand/oozy sediment. We have chosen to use five cm as the active layer which the cuttings will be blended into. If 1.8 mm of cuttings are blending into the five cm bioactive sediment, the concentration will be diluted 28 times. This value has been used to calculate the PEC/PNEC. Table 30 presents calculations based on the PNECs from the Norwegian Environment Agency (Weideborg *et al*, 2012) and OSPAR (2012), while Table 31presents calculations based on Altin *et al* (2008).

Table 30. PEC/PNEC calculations for the priority pollutants identified in treated cuttings. The calculations utilise PNEC values from the Norwegian Environmental Agency (Weideborg et al, 2012) and OSPAR (2012).

Analysis parameter	PNEC sediment (mg/kg)	PEC/PNEC cuttings (no dilution)				PEC/PNEC sediment (diluted 28 times)			
		Out 38	Out 41	Out 17	Out C	Out 38	Out 41	Out 17	Out C
Oil									
THC >C_5-C_8	1.25	**8.0**	**9.6**	**6.0**	<4.0	0.29	0.34	0.21	<0.14
THC >C_8-C_{10}	22.4	0.98	**1.29**	0.67	0.85	0.035	0.046	0.024	0.030
THC >C_{10}-C_{12}	175	0.16	0.19	0.15	0.38	0.006	0.007	0.006	0.013
THC >C_{12}-C_{16}	3500	0.069	0.11	0.20	0.17	0.002	0.004	0.007	0.006
THC >C_{16}-C_{35}	7000	0.17	0.31	0.50	0.026	0.006	0.011	0.018	0.001
PAH_{16}									
Naphthalene	0.027	<0.02	<0.02	**9.3**	**1.07**	<7E-04	<7E-04	0.33	0.038
Acenaphthylene	0.033	<0.02	<0.02	0.33	0.24	<5E-04	<5E-04	0.012	0.009
Acenaphthene	0.16	<0.003	<0.003	**1.13**	0.081	<1E-04	<1E-04	0.040	0.003
Fluorine	0.26	<0.002	<0.002	0.092	0.028	<7E-05	<7E-05	0.003	0.001
Phenanthrene	0.5	<0.001	<0.001	0.34	0.032	<4E-05	<4E-05	0.012	0.001
Anthracene	0.0048	<0.1	<0.1	4.79	0.60	<0.004	<0.004	0.171	0.022
Fluoranthene	0.117	<0.004	<0.004	0.38	0.07	<2E-04	<2E-04	0.014	0.002
Pyrene	0.014	<0.04	<0.04	6.50	1.21	<0.001	<0.001	0.232	0.043
Benzo[a]anthracene	0.06	0.10	0.20	0.58	0.37	0.004	0.007	0.021	0.013
Chrysene/triphenylene	0.28	<0.002	0.01	0.20	0.08	<6E-05	2.9E-04	0.007	0.003
Benzo[b,j,k]fluoranthene	0.14	0.03	0.10	0.32	0.21	0.001	0.004	0.011	0.007
Benzo[a]pyrene	0.18	0.01	0.02	0.16	0.11	4.4E-04	0.001	0.006	0.004
Indeno[1,2,3-cd]pyrene	0.063	0.06	0.17	0.32	1.16	0.002	0.006	0.011	0.041
Dibenzo[a,h]anthracene	0.027	0.11	0.16	0.24	0.78	0.004	0.006	0.009	0.028
Benzo[ghi]perylene	0.084	0.05	0.08	0.14	1.19	0.002	0.003	0.005	0.043
Metals									
Arsenic	47	0.09	0.12	0.18	0.17	0.003	0.004	0.006	0.006
Barium[1]	848	**9.20**	**8.14**	0.19	0.60	0.33	0.29	0.007	0.021
Lead	150	0.19	0.15	0.20	0.14	0.007	0.005	0.007	0.005
Cadmium	2.5	0.032	0.088	0.052	0.052	0.001	0.003	0.002	0.002
Copper	84	**2.14**	0.49	0.30	0.37	0.077	0.017	0.011	0.013
Chromium	620	0.04	0.05	0.04	0.04	0.001	0.002	0.001	0.001
Mercury	0.52	0.13	0.17	0.05	0.02	0.005	0.006	0.002	0.001
Nickel	43	0.63	0.72	0.60	0.40	0.022	0.026	0.022	0.014
Zinc	340	0.59	0.41	0.16	0.25	0.021	0.015	0.006	0.009

[1] Barium PNEC from Altin et al (2008).

Table 31. PEC/PNEC calculations of the priority pollutants identified in treated cuttings. Calculations conducted with field-specific PNEC values supplemented by background values (from Altin et al, 2008).

Analysis parameter	PNEC (mg/kg)	PEC/PNEC cuttings (no dilution)				PEC/PNEC sediment (diluted 28 times)			
		Out 38	Out 41	Out 17	Out C	Out 38	Out 41	Out 17	Out C
Oil									
THC	318.5	**4.7**	**8.3**	**13**	**2.7**	0.17	0.30	0.48	<0.10
PAH_{16}									
Naphthalene	2.05	$<2.10^{-4}$	$<2.10^{-4}$	0.12	0.014	10^{-5}	10^{-5}	0.004	0.0005
2-3 ring PAH	0.11	<0.03	<0.03	**4.1**	0.50	0.001	0.001	0.15	0.02
4+ ring PAH	0.4	0.06	0.13	0.74	0.76	0.002	0.005	0.03	0.027
Metals									
Barium	848	**9.20**	**8.14**	**0.19**	**0.60**	0.33	0.29	0.007	0.021
Arsenic	-	-	-	-	-	-	-	-	-
Lead	21.6	**1.3**	**1.1**	**1.4**	**1.0**	0.05	0.04	0.05	0.03

Cadmium	0.077	**1.0**	**2.9**	**1.7**	**1.7**	0.04	0.10	0.06	0.06
Copper	8.23	**22**	**5.0**	**3.0**	**3.8**	0.78	0.18	0.11	0.13
Chromium	24.68	**1.0**	**1.1**	**1.0**	**0.89**	0.03	0.04	0.03	0.03
Mercury	0.125	**0.56**	**0.70**	**0.20**	**0.06**	0.02	0.02	0.01	0.002
Nickel	-	**-**	**-**	**-**	**-**	-	-	-	-
Zinc	41.86	**4.8**	**3.3**	**1.3**	**2.1**	0.17	0.12	0.05	0.07

Where oil is concerned, assessments based on Altin *et al* (2008) will provide a higher or lower PEC/PNEC, depending on the quantity of the various aliphatic fractions present. But the order of magnitude will be the same for both calculation methods.

Altin's PNEC value for naphthalene is more than 70 times higher than the Norwegian Environment Agency's PNEC. The PEP/PNEC is therefore correspondingly lower. Where the other PAHs are concerned, the two sets of PNECs give PEC/PNEC calculations in the same order of magnitude.

Altin's values give much higher PEC/PNECs than the Norwegian Environment Agency's values for all heavy metals except for mercury. Nickel was not assessed by Altin et al.

If the PEC/PNEC is > 1, the environmental risk is unacceptable pursuant to the EU's Guidelines. As shown in Table 30 and Table 31, a number of substances in undiluted treated cuttings will occur in concentrations which provide an unacceptable environmental risk. In an estimated "worst case" dilution, none of the substances will pose an environmental risk. That applies regardless of which of the two PNEC sets is used

6.4.3. *Corophium* and the effect of seabed smothering

A TU can be calculated for cuttings in the same way as for leachate. Nevertheless, finding good LD_{50} values for sediment-dwelling organisms can be problematic. Where many substances are concerned, the PNEC for sediment has been estimated on the basis of water toxicity and the sediment/water distribution coefficient (K_d). This approach assumes that the toxicity of the substances involved is the same as for leachate and, on the basis of the *Calanus finmarchicus* results, particles will represent as high a risk as leaching in the water column.

Corophium was tested for cuttings concentrations of 10-100 per cent in the sediment. At these concentrations, physical disturbance is expected to be very considerable. A maximum concentration of 5 cm/1.8 mm = 3.6 per cent would be expected in the environment. No elevated mortality of *Corophium* is to be expected at that concentration, but the organisms will probably move from the most polluted area.

Sessile organisms such as corals will be exposed to smothering. Compared with the results from Bakke et al (2012), which demonstrate that the *Lophelia pertusa* coral species has proved capable of removing 6 mm of sludge, the calculated 1.8 mm layer of cuttings should have no effect on these organisms.

No disturbance of the benthic fauna can be demonstrated with the anticipated maximum concentration in the environment, but a possible limited effect cannot be excluded. No long-term effect on the population is anticipated, but negative effects on vulnerable benthic species cannot be excluded.

6.5. Environmental risk compared with WBM cuttings

6.5.1. WBM versus treated OBM cuttings

As noted in Chapter 3, many studies are available on the environmental effects of WBM cuttings. The two types of cuttings can be expected to have comparable effects on the

environment. Differences could nevertheless occur because of variations in chemical composition or differing particle sizes.

6.5.2. NIVA's evaluation

T Bakke at NIVA has conducted an independent assessment of raw data from this study in a Technical Note (Appendix 11). The results of toxicity testing were compared with information on WBM cuttings from the following references, among others:

- various reports on sediment monitoring around Norwegian petroleum installations
- Trannum, H (2011); Bakke et al (2013) and Bechmann et al (2006).

Bakke describes four different forms of exposure to marine organisms which can occur from discharging TCC-treated OBM cuttings to the marine environment:

- Leaching of substances through desorption from suspended cuttings particles to the body of water
- Corresponding leaching from sedimented particles to pore water
- Physical load of suspended particles on pelagic organisms
- Physical load on benthic organisms.

The tests for MARA, Microtox, alga and *Acartia* were conducted with leachate, where the same leachate was analysed for polluting substances (see Chapter 5). The cuttings were blended in water for a day, sedimented for a day and then filtered (see Section 4.2.4). All these tests concentrated on investigating the effects of leached substances desorbed from suspended cuttings particles in the body of water

The *Calanus* test was conducted in two series, one with particles present in the water and one without particles, prepared in a similar way as leachate. The test with particles only used short sedimentation to remove the largest particles which are assumed to sediment very quickly and could not therefore impose a load on the organisms (see Altin's report in the Appendix for details). This test investigated the effect of the physical load of suspended particles on pelagic organisms.

The *Corophium* test was conducted on sediment and involved exposure to particles from sedimented cuttings and leaching from sedimented particles into the pore water.

Bakke's comparison of the environmental effects of discharging thermal treated OBM cuttings and untreated WBM cuttings provided valuable information, and he concludes that the effects of the two types of cuttings on the natural environment and benthic habitats are unlikely to be significantly different. He recommends the use of mesocosmic studies to back up this conclusion, particularly with regard to benthic organisms. Bakke's conclusion does not differ significantly from ours. One comment with regard to mesocosmic studies is the uncertainty about the quantity of cuttings which the benthic organisms should be exposed to in such a test. The dilution studies conducted by SINTEF show that the quantity of thermal treated cuttings which become deposited on the seabed is significantly less than the amount of WBM cuttings. It is therefore difficult to undertake direct comparisons related to the exposure quantity.

7. Conclusions and further recommendations

Based on sampling and analyses of four different sets of thermal treated OBM cuttings samples (inlet and outlet) from a TCC reactor, it can be concluded that the technology cleans the cuttings in accordance with the data provided by the supplier. The comparison of measured results when using the technology in onshore plants with those documented from offshore use suggests that it is at least as effective offshore, where the cuttings samples are fresh when treated, as when they have been transported and stored before treatment onshore. The average oil content in cuttings treated offshore is reported to be 0.4 g/kg dm, while measurement of the four samples from land-based treatment shows a range from 0.86 to 4.3 g/kg dm – which is still in line with the supplier's specifications.

The cuttings samples have been studied for particle size and physical/chemical properties. All four samples contain a sizeable proportion of clay in the cuttings. Thermal treatment reduces particle size and increases the proportion of fine powder compared with untreated cuttings.

Analyses of leachate, particles in suspension and toxicity tests are summarised in Table 32 and Figure 43. Copper is the substance which poses the highest environmental risk in undiluted leachate. With expected dilution (based on modelling of discharges from the rig when drilling and exploration well on the Ivar Aasen field, 113 metres of water and discharge at one metre beneath the sea surface) in the recipient, no chemical substances will pose an environmental risk in either the sediment or the water column (based on leaching and the total quantity of cuttings). Toxicity tests confirm the theoretical assessments made on the basis of chemical analyses.

Tests of *Calanus finmarchicus* with and without exposure to particles show that particles in the water have a negative effect on the organisms. Since the cuttings do not contain sharp particles, we assume that the effect is due to the consumption of small particles which can have a toxic effect or fill the gut and prevent further uptake of nutrients. The effect was measured at a concentration which was 1000 times higher than the anticipated concentration in the environment and is accordingly not expected in the environment. More detailed studies of the test results show that the high particle concentrations have produced high oxygen consumption in the samples and increased their pH (highest measured pH was 9.2). The effect may be due to chemical oxygen consumption which has yielded < 20 % oxygen saturation in the samples during the test rather than the concentration of particles. The limit of *Calanus finmarchicus*' tolerance for oxygen and pH is not known.

Table 32. Summary of parameters for leachate and water with particles in suspension. The colour code accords with Weideborg et al (2012): blue = background, green = good, yellow = moderate = orange = poor and red = very poor.

Parameter	Out 38	Out 41	Out 17	Out C
Chemical analyses of leachate				
Oil (total of C_5-C_{35})	420 µg/l	380 µg/l	68 µg/l	41 µg/l
PAH (total of 16 PAH)	0.35 µg/l	0.06 µg/l	0.17 µg/l	0.092 µg/l
Barium	110 µg/l	94 µg/l	140 µg/l	140v
Arsenic	2.60 µg/l	2.3 µg/l	16 µg/l	< 1 µg/l
Lead	0.71 µg/l	0.31 µg/l	< 0.2 µg/l	0.26 µg/l
Cadmium	< 0.2 µg/l	< 0.2 µg/l	< 0.2 µg/l	< 0.2 µg/l
Copper	59 µg/l	46 µg/	17 µg/l	26 µg/l
Chromium	9 µg/l	10 µg/l	2.4 µg/l	3 µg/l
Mercury	< 0.05 µg/l	< 0.05 µg/l	0.08 µg/l	< 0.05 µg/l
Nickel	46 µg/l	40 µg/l	46 µg/l	45 µg/l
Zinc	3.2 µg/l	3.1 µg/l	10 µg/l	6.1 µg/l
Maximum PEC/PNEC with leaching				
Oil	6.00	5.43	0.97	0.59

Parameter	Out 38	Out 41	Out 17	Out C
PAH	<10	<10	<10	<10
Metals and barium	23	18	7	10
Maximum PEC/PNEC in recipient (diluted 20 000 times)				
Oil	0.0003	0.0003	0.00005	0.00003
PAH	<0.0005	<0.0005	<0.0005	<0.0005
Metals and barium	0.0011	0.0009	0.0003	0.0005
Maximum PEC/PNEC in recipient if cuttings included (max 5 ppm cuttings in water column)				
Oil	0.0011	0.0019	0.0031	0.0006
PAH	0.0001	0.0002	0.0004	0.0014
Metals and barium	0.0035	0.0021	0.0013	0.0013
Toxicity				
Calculated EC_{50} leachate	8%	10%	23%	17%
Lowest measured EC_{50} leachate	18%	18%	29%	15%
EC_{50} *Calanus* - with particles - without particles	 >20 g/l 8 g/l	 >20 g/l 8 g/l	 >20 g/l 8 g/l	 >20 g/l 8 g/l

Analysis of treated cuttings, calculated PEC/PNEC in the sediment and the comparison with results from toxicity tests conducted for sediment mixed with cuttings are summarised in Table 33. Barium will pose the highest environmental risk for undiluted sediment with undiluted cuttings in samples Out 38 and Out 41. Naphthalene will pose the highest risk in samples Out 17 and Out C calculated as PEC/PNEC. With expected concentrations in the sediment, none of the substances will pose an environmental risk. *Corophium* reveals a toxic effect at concentrations which are in the order of 10 times higher than the anticipated environmental concentration (based on the maximum concentration determined by SINTEF's modelling of dispersion on Ivar Aasen).

The difference is not large enough to be able to exclude negative effects from cuttings discharges on sediment-dwelling organisms.

Table 33. Summary of the measured composition of treated cuttings with sediment. The colour code accords with Weideborg et al (2012): blue = background, green = good, yellow = moderate = orange = poor and red = very poor.

Parameter	Out 38	Out 41	Out 17	Out C
Chemical analysis of cuttings (mg/kg dm)				
Oil (total of C_5-C_{35})	1500	2700	4300	860
PAH (total of 16 PAH)	0.023	0.053	1	0.39
Barium	7 800	6 900	160	510
Arsenic	4	5.6	8.4	7.8
Lead	28	23	30	21
Cadmium	0.08	0.22	0.13	0.13
Copper	180	41	25	31
Chromium	24	28	24	22
Mercury	0.07	0.087	0.025	0.008
Nickel	27	31	26	17
Zinc	200	140	55	86
Maximum PEC/PNEC[1] in cuttings (no dilution)				
Oil	8.0–4.7	9.6–8.3	6.0–13	<4–2.7
PAH	0.11–0.06	<0.2–0.13	9.3–4.1	1.2–0.76
Metals	2.14–22	0.72–5.0	0.60–3.0	0.40–3.8
Barium	9.2	8.1	0.19	0.60
Maximum PEC/PNEC[1] in sediment (diluted 28 times)				
Oil	0.29–0.17	0.34–0.30	0.21–0.48	<0.14–0.10
PAH	0.004–0.002	0.007–0.005	0.33–0.15	0.043–0.03

Metals	0.08–0.78	0.03–0.18	0.022–0.11	0.021–0.13
Barium	0.33	0.29	0.007	0.02
Toxicity				
LC_{50} *Corophium*	50 %	63 %	>100 %	about 100 %

[1] Two sets of PNECs were used in this calculation, resulting in two sets of PEC/PNECs.

Based on sampling, analyses and environmental risk assessment of offshore discharges for heat-treated OBM cuttings to the sea, compared with the results of monitoring and studies conducted on the effect of discharging WBM cuttings, the following conclusions can be drawn.

- Environmental risk associated with discharges of thermal treated OBM cuttings will correspond to that seen with discharges of WBM cuttings.
- The levels of oil, PAH and metals in treated OBM cuttings are expected to be similar to those in WBM cuttings.
- The only environment-related footprints which might be identified through monitoring relate to particles and smothering with sludge in areas with the highest sedimentation rate by cuttings. Chemical pollution is expected to have a negligible effect on both pelagic and benthic organisms. No effects are expected in the water column.
- Because particles of thermal treated cuttings are somewhat smaller than for WBM cuttings, smothering with sludge on the seabed is expected to be less.

However, these conclusions should be verified by the following surveys:

- Follow-up of installations on the NCS
  - mapping discharges of cuttings, oil and water
  - modelling dispersion of discharges
  - carrying out risk assessments based on actual discharges.
- Background data from environmental monitoring in 2012 should be reviewed, and PNEC values and ESQs prepared for the water column and sediment in various regions of the North Sea.
- Sources of heavy metals in sediments/cuttings should be investigated. Different barite types should be analysed for heavy metals. Should big differences be found, checks should be made to establish whether these can explain differences in background values in different parts of the North Sea. The need to establish required specifications for barite should be considered.
- The reasons for oxygen consumption by cuttings in ecotoxicity tests should be clarified, and toleration limits for oxygen and pH by *Calanus finmarchicus* and *Corophium* identified with a view to utilising this type of test in following up studies of the effect of cuttings dispersion.

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